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COMPILATION OF

MATERIALS RESEARCH DATA

FOURTH QUARTERLY PROGRESS REPORT-PHASE I

1 December 1961 to 1 February 1962

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TASK NO. 73812

Prepared by P. Bergstedt
P. Bergstedt
Sr. Engineering Metallurgist

Approved by A. Hurlich
A. Hurlich
Research Group Engineer
Materials Research Group

Approved by V. A. Babits
V. A. Babits
Manager of Research

Approved by W. H. Schmidtetley for
H. F. Dunholter
Asst. Chief Engineer
Development

ABSTRACT

This Fourth Quarterly Progress Report under Contract AF 33(616) -7984 consists of a collection of twelve internal reports generated in materials investigations at General Dynamics/Astronautics. At the customer's request, the individual reports are submitted in their entirety rather than in condensed form, and the compilation has been assigned a report number (AE62-0138-3) for reference purposes.

Mechanical properties of metals constitute the bulk of this progress report; included are data on commercially pure titanium and eight titanium alloys, several aluminum alloys in various cold worked and/or heat treated conditions, Type 301 stainless steel, 20% and 25% nickel steels, and Rene 41 nickel-base alloy. Cryogenic testing has been emphasized in most of this work.

Subsequent sections of the progress report contain single reports concerning tensile properties of structural plastics at low temperature, x-ray diffraction studies of martensite content in Type 301 stainless steel, and linear expansion determinations at low temperatures on Polycel 420 and Conolon 506.

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Section 1 - Mechanical Properties of Metals

SUBJECT: Final Report on the Evaluation of Chemical Milling as a Possible Process Technique in the Production of ½- Hard and 3/4- Hard 301 Stainless Steel Bulkheads.

ABSTRACT

The effect of the chemical milling process on the tensile and fatigue properties, corrosion resistance, thickness tolerance, etc., of base metal and weld joints of stretch-formed Type 301 cold worked stainless steel sheet has been evaluated. Three major deterrents to the use of chemical milling as a fabrication technique were established by this work. First, the fatigue properties of the base metal and the heliarc weld joints appeared to be considerably reduced. Second, hydrogen embrittlement was found to exist in the metal after the chem-milling process and this could not be completely relieved without resorting to a vacuum degassing treatment. Third, corrosion resistance was decreased markedly. Thickness tolerances were kept within 0.001 inch with a surface finish between 60 and 120 rms. A preferential acid attack resulted in undercutting of the weld area. However, this could be overcome by appropriate masking techniques.

Prepared by: R. L. Jones
R. L. Jones

Approved by: A. Hurlich
A. Hurlich
Research Group Engineer
Materials Research Group

AH:RLJ:vea

Distribution:

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FROM: Materials Research Group, 595-2

SUBJECT: Final Report on the Evaluation of Chemical Milling as a Possible Process Technique in the Production of ½- Hard and 3/4-Hard 301 Stainless Steel Bulkheads.

INTRODUCTION

At the request of the Structural Design Group, a study was initiated to evaluate the effects of chemical milling on the mechanical properties, corrosion resistance, surface finish, thickness tolerance, etc., of ½-H and 3/4-H 301 stainless steel bulkhead sections.

In order to evaluate this processing technique correctly, it was decided to have the chemical milling performed by a reputable vendor rather than attempt a laboratory simulation of the process. Although this has led to considerable delay, it is by far the most satisfactory approach.

A progress report on this evaluation program was issued on 29 March 1960 (Report No. MRG-144). The results of thickness tolerance and surface finish measurements visual, x-ray and metallographic examinations as well as hydrogen embrittlement studies were presented.

It is the purpose of this report to present the results of the remainder of the program. These are concerned with mechanical properties such as tensile and fatigue, corrosion properties and means of relieving hydrogen embrittlement.

However, before proceeding to the results and discussion of the current phases of the program it would be well to review the major conclusions presented in the first progress report. These are as follows:

1. In general, thickness variations are increased by chemical milling but it appears that these variations can be kept on within 0.001 inch in the present case.

2. The surface finish was decreased from 17 rms as stretched-formed to between 60 and 120 rms after chemical milling.

3. Careful examination indicated that no unusual chemical attack occurred in the areas of high Lüeder line areas.

4. X-ray examination showed that the weld areas were sound before and after chemical milling.

5. After a 50-percent reduction in base metal thickness by chemical milling, the thickness variation in the nugget was increased. Furthermore, a selective attack was also noted in the heat-affected zones. After chemical milling, the heat-affected zones were thinner than the base metal by about 9 percent. The minimum thickness in the nugget area was as much as 27 percent thinner than the base metal.

6. It was found that this material was hydrogen embrittled by the chemical milling process, but the severity of this embrittlement could not be determined.

Obviously, the two major effects of chemical milling uncovered during the initial phase of this study are associated with the selective attack of the weld nugget and heat-affected zones and the introduction of hydrogen embrittlement. It was suggested that it is possible to overcome the thinning problem (selective attack of the heat-affected zone and weld nugget) by removing the bulkhead sections from the chemical milling solution when a few thousandths of metal remain to be removed. The weld area could then be masked and the remaining metal removed from the bulkheads.

Techniques for decreasing the severity of hydrogen embrittlement were established during this phase of the study and will be reported on in the sections that follow.

RESULTS AND DISCUSSION

Partial bulkhead sections made from stretch-formed ½- Hard and 3/4- Hard 301 stainless steel were chemically milled from 0.020 (or 0.025) inch thickness to 0.010 inch by the United States Chemical Milling Corporation. Standard tensile coupons were machined from both bulkhead sections. Both base metal and weld coupons were obtained. Samples of the chemically milled bulkheads 3" x 3" were removed for salt spray corrosion tests.

TENSILE TESTS

Tensile tests were performed at room temperatures. Tests were run on samples machined from the weld areas such that the heliarc butt weld was in the center of the reduced section and was perpendicular to the length of the tensile coupon. Samples for base metal property evaluation were also obtained from the bulkhead sections away from the welded area but in the same direction as the weld test coupon. Triplicate samples were prepared and tested.

As shown in Table 1, the tensile properties were essentially unaffected by the chemical milling process. The small variations that are observed can be attributed to several factors. The unchem-milled samples were 0.020 inch thick while the chemical milled test coupons were only 0.010 inch. Over and above the thickness effects that may be introduced, normal scatter and test

accuracy would account for most if not all of the differences observed, especially on samples taken from a stretch-formed bulkhead section.

FATIGUE TESTS

Extra samples had been machined for the tensile test phase of this study. Because they were not needed for tensile testing it was decided to use them for a preliminary evaluation of fatigue properties. Since these coupons were not the best specimen configuration for a fatigue test, it was anticipated that some trouble might be experienced in the testing phase. This proved to be true since some of the coupons failed at one end of the reduced section or the other instead of in the central portion for which accurate dimensions were known. In spite of this problem the data of Table 2 appear to show some significant trends.

The data of Table 2 were obtained from tension-tension tests on a Baldwin-Tate-Emery (SF-1-U) fatigue tester. In general the data presented are the average of duplicate tests, but in some cases triplicate tests were obtained. As in the case of tensile testing, the properties of the chemically milled bulkheads were developed on samples 0.010 inch thick whereas the original metal properties were obtained on metal of .020 (or .025) inch thickness. Alignment and dimensional measurements of the thin samples were very difficult to attain accurately, especially in the weld areas. Despite the problems of alignment, dimensional accuracy, and small sample size, the large decrease in the number of cycles to failure after chemical milling strongly suggests that fatigue properties are indeed effected adversely by the chem-mill process.

CORROSION RESISTANCE

The corrosion resistance of the chemical milled surface was not known and it appeared that a preliminary investigation of this problem should be undertaken. Test panels as shown below were subjected to salt spray tests for 1000 hours duration:

1. Control - surface as-stretch-formed
2. Chemically-milled
3. Chemically-milled plus passivated in HNO_3 solution

As expected, the control panel survived this test readily with only a few easily removed surface stains being observed. The chemically milled surfaces showed a more general staining but this too was easily removed.

However, two or three isolated points which were severely attacked were noted. In these areas, corrosion resulted in complete penetration of the 0.010 sheet and a small pin hole was formed. This pin hole corrosion occurred on the passivated samples as well as the unpassivated sample.

HYDROGEN EMBRITTLEMENT

Because of the thinness of the bulkhead sections hydrogen embrittlement tests could not be performed on this material. However, samples of 0.060 full hard 301 stainless steel were submitted to the vendor along with the bulkhead sections. The vendor chem-milled these samples to 0.040 and returned them for test. As mentioned in the first report, these samples were embrittled by the chem-mill process.

Hydrogen embrittlement of heat-treated low alloy steels can be relieved by a low temperature baking treatment and consequently, processes which introduce embrittlement in these steels can be used if the materials are baked after the process has been employed.

Attempts were made to eliminate the hydrogen embrittlement of 301 stainless steel introduced by the chem-mill process by various baking treatments. It proved impossible to completely eliminate the hydrogen embrittlement even at temperatures up to 500°F. It was felt that higher baking temperatures might affect the base metal properties. Therefore, vacuum degassing treatments were investigated as a possible means of eliminating the hydrogen. It was found that vacuum degassing at room temperature with a relatively poor vacuum (30-50 microns) completely eliminated the hydrogen embrittlement introduced from the chemical milling process.

Unfortunately, it is not possible to specify at this time what degree of hydrogen embrittlement can be tolerated in the 301 stainless steel without leading to catastrophic failure. Vacuum degassing of 10' diameter bulkheads is not a desirable or even very feasible production process. An 8 hour bake at 400°F could be carried out but some degree of hydrogen embrittlement will remain.

CONCLUSIONS

Based on a limited amount of data, the following conclusions can be drawn regarding the effect of chemical milling on the static, fatigue, and corrosion properties of ½ and 3/4 hard 301 stainless steel bulkhead material.

1. Tensile properties (F_{tu}, F_{ty} , E, e) remain essentially unaffected.

2. Fatigue properties (cycles to failure) appear to be reduced considerably.

3. General resistance to corrosion is reduced slightly but the

resistance to localized attack such as pin-hole corrosion is markedly reduced.

4. Hydrogen embrittlement, introduced during the milling process can be reduced considerably by a baking treatment of 8 hours at 400°F or completely eliminated by vacuum degassing at room temperatures.

RECOMMENDATIONS

The results of this investigation show that chemical milling affects the properties of 301 bulkhead material in several respects. Before using materials processed in this manner a complete evaluation of these effects are necessary, since design allowables may be changed considerably, especially fatigue allowables.

Because of the undue amount of testing necessary to establish new design allowables on 301 stainless processed by the chem-milling technique, it is recommended that the process be used only when it is not possible to obtain the final product by more conventional means.

If it is necessary to use the chem-mill process, further investigation of fatigue properties, corrosion resistance and hydrogen embrittlement is strongly recommended. However, the deleterious effects of this process upon the fatigue and corrosion resistance of cold worked and stretch-formed Type 301 stainless steel sheet would indicate that other methods of effecting weight reductions should be more thoroughly investigated before chem-milling is selected as the production process.

Table 1

TENSILE DATA AT ROOM TEMPERATURE FOR 301 STAINLESS STEEL BULKHEADS

BEFORE AND AFTER CHEMICAL MILLING

Material	F_{tu}	F_{ty}	e	E
Prior to Chem-Mill	psi	psi	percent	psi
½ Hard Base Metal	187,000	126,000	20.7	25.9×10^6
½ Hard Weld Metal	127,000	-		
3/4 Hard Base Metal	204,000	170,000	5.0	26.5×10^6
3/4 Hard Weld Metal	138,000	-		
After Chem-Mill				
½ Hard Base Metal	189,000	158,000	14.7	24.4×10^6
½ Hard Weld Metal	138,000	-		
3/4 Hard Base Metal	201,000	169,000	6.5	24.6×10^6
3/4 Hard Weld Metal	135,000	-		

Table 2

FATIGUE DATA AT ROOM TEMPERATURE FOR 301 STAINLESS STEEL BULKHEAD SECTIONS BEFORE AND AFTER CHEMICAL MILLING

MATERIAL	STRESS LEVEL TENSION-TENSION FATIGUE	CYCLES TO FAILURE
Prior to Chem-Mill		
½ Hard - Base	120,000 psi max.-10,000 psi min.	160,000
½ Hard - Weld	80,000 psi max.-10,000 psi min.	201,000
3/4 Hard - Base	130,000 psi max.-10,000 psi min.	86,000
3/4 Hard - Weld	80,000 psi max.-10,000 psi min.	148,000
After Chem-Mill		
½ Hard - Base	120,000 psi max.-10,000 psi min.	80,000
½ Hard - Weld	80,000 psi max.-10,000 psi min.	16,000
3/4 Hard - Base	130,000 psi max.-10,000 psi min.	30,000
3/4 Hard - Weld	80,000 psi max.-10,000 psi min.	36,000

SUBJECT: Properties of R-41 Sheet, A Vacuum Melted, Nickel Base Alloy

ABSTRACT

The mechanical properties (F_{ty}, F_{tu}, elongation, and notched/unnotched tensile ratios) were determined at +78, -100, -320, and -423°F on R-41 (Rene 41) 0.020" sheet material in both the as-received and age-hardened conditions. The data indicate that R-41 sheet metal in the age-hardened condition remains tough at cryogenic temperature as determined by notched/unnotched tensile ratios. R-41 alloy is one of the highest strength materials available for structural applications at 1600-1800°F, and would thus be especially suitable for applications where the same component would be exposed initially to liquid oxygen or liquid hydrogen temperatures and then undergo heating in service to elevated temperatures while subjected to high stresses. Supplementary information on the chemistry, available forms, heat treatments, fabrication (forging, welding, machining, etc.), and physical and mechanical property data is included. Seven references on R-41 alloy which are available in the Materials Research Group are listed in Appendix A.

Prepared by: J. L. Christian
J. L. Christian

J. F. Watson
J. F. Watson

Approved by: A. Hurlich
A. Hurlich
Research Group Engineer
Materials Research Group

AH:JFW:JLC:js

Distribution:

W. F. Radcliffe, 595-0
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J. Comber, 541-3
W. Gross, 563-1

MATERIALS

The R-41, a vacuum melted, nickel base alloy, used in this investigation was supplied by Haynes Stellite Company, in 0.020" thick sheet, heat number TV-592.

The material was received in the solution treated (1975°F rapid quench) condition. Chemical composition limits for R-41 wrought and cast alloys as well as the certified chemical analysis of the material used in this investigation are presented in Table 1. The as-received material had a R_b hardness of 93. Part of the material was solution treated (1950°F for 30 min., air cool) and age-hardened (1400°F for 16 hours, air cool) under an inert atmosphere by Materials Research Group heat treat facilities. Very little or no surface tarnish resulted from heat treatment. Hardness was R_c 39. Mechanical property data determined at room temperature by the Materials Research Group duplicated the certified data supplied by the vendor.

PROCEDURE

Blanks for tensile specimens, 9" x 1½", were identified and sheared in directions both longitudinal and transverse to the direction of rolling. Half of the specimen blanks were age-hardened, and both smooth (EMG-D-1) and notched (MRG-D-10, Notch "A") tensile specimens were machined. A minimum of three tensile tests in the longitudinal and two tests in the transverse directions were performed on both smooth and notched specimens at room temperature (78°F), -100°F (alcohol and dry ice), -320°F (liquid nitrogen), and -423°F (liquid hydrogen). Strain measurements were made by use of extensometers (cryo-extensometer at low temperatures) and a continuous stress strain recorder. Total elongation was determined by scribe marks made with a precision block and read under 10X magnification. Strain rates were maintained at 0.001"/"/min. until 0.2% offset yield and then 0.15"/min. until fracture. The 50,000# Baldwin testing machine, strain recorder, strain pacer, and extensometers are periodically checked and approved by CVA standards laboratory.

RESULTS AND DISCUSSION

The results of the mechanical property testing on the as-received material are presented in Table 2. As may be seen, the solution treated R-41 sheet material suffers from rather low notched/unnotched tensile ratios at all testing temperatures. Also, a large scatter exists in the notched tensile data at -423°F, this being indicative of embrittlement. The low yield and tensile strengths of the as-received R-41 alloy make it unfavorable for applications requiring a material with high strength/density.

The mechanical properties of the age-hardened R-41 sheet material at +78, -100, -320, and -423°F are presented in Table 3. The notched/ unnotched tensile ratio increases from 0.91 at 78°F to 0.99 at -423°F. These data plus the increase of notched tensile strength with reduction in temperature and good ductility as measured by elongation indicate that R-41 sheet in the age-hardened condition remains tough from room temperature to nearly absolute zero. The relatively high yield (134-138 ksi) and tensile (174-181 ksi) strengths at 78°F makes R-41 alloy competitive with other materials. The density of R-41 is 0.296 pounds/in^3 (density of 301 CRES is 0.288 #/in^3). For those applications which require a structural material to be used at both high and very low temperatures, R-41 alloy is most attractive.

SUPPLEMENTARY INFORMATION

R-41 alloy is available as sheet, plate, bar, wire, or forging stock as well as investment castings (see Table 4) at a cost comparable with many other nickel or cobalt base and titanium base alloys.

A variety of heat treatments have been successfully employed, the more common of which are listed below.

A. Solution treat at 1975° ± 25°F, rapid quench. (Normal "as-received" condition)

B. Heat treatment A plus solution treat at 1950°F for 30 min., air cool; age at 1400°F for 16 hours, air cool.

C. Heat treatment A plus solution treat at 2150°F for 30 min., air cool; age at 1650°F for 4 hours, air cool.

Rapid quenching instead of air cooling for heat treatments B and C have shown some advantages, especially for cast material. In general, higher solutioning temperatures result in better room temperature ductility and higher rupture strength at elevated temperatures, whereas lower solutioning temperatures result in higher tensile strengths. The material may be annealed for maximum formability by treating it at 2150°F for 30 min., water quench. Stress relieving after machining, cold working, or welding may be obtained by re-solutioning with subsequent aging if desired.

R-41 is one of the strongest high temperature materials that can be successfully formed and welded(references, Appendix A). The alloy may be readily formed in the annealed condition. Distortion is comparatively low if the material is subsequently solution treated.

R-41 may be successfully forged, however small reductions should be taken. Starting temperature should be 2150°F (2195°F max.) and finishing temperature 1950°F min. to prevent cracking. The alloy has been successfully cast. Cold working with subsequent heat treatment improves the as-cast mechanical properties.

The alloy may be machined (preferably in the fully aged condition since the soft solutioned condition is "gummy") by either carbide or high speed tools. Tool geometry, depth of cut, feed, and speed are available for satisfactory machining. R-41 can be inert-arc welded, manually or by machine, and with or without filler metal. Spot welds can be made on conventional equipment. Properly performed welds are ductible, 90% efficient, and are not crack sensitive. Welding should be done in the fully solutioned condition with subsequent solution treatment for homogenization and stress relief followed by aging for maximum strength.

A large amount of physical and mechanical property data on R-41 alloy are available. Tensile, fatigue, creep, creep-rupture, and elastic properties are available at various temperatures (generally 70° to 1800°F). The alloy is highly corrosion and oxidation resistant.

SUMMARY

1. R-41 sheet material in the solution treated condition shows little promise for structural applications at cryogenic temperatures due to embrittlement and low yield strengths.

2. R-41 sheet material in the age hardened condition (1950°F, 30 min., air cool) has a high strength/density ratio and remains tough at very low temperatures, as determined by notched/unnotched data, fracture appearance, and ductility.

3. R-41 alloy is commercially available in many forms at costs comparable with other engineering materials.

4. R-41 alloy has attractive physical and mechanical properties (tensile, creep, creep-rupture, fatigue, elastic, etc.).

5. R-41 alloy is one of the highest strength materials available in the 1600°-1800°F temperature range.

6. R-41 alloy is highly corrosion and oxidation resistant.

7. R-41 alloy may be readily formed and fusion or spot welded with available production equipment.

TABLE 1

Chemical Compositions of R-41

Alloying Element	Wrought Alloy* Limits,%	Cast Alloy* Limits,%	Material Used in This Investigation Heat TV-592
Chromium	18.00-20.00	18.00-20.00	19.54
Iron	5.00 max.	5.00 max.	0.46
Carbon	0.12 max.	0.06-0.12	0.09
Silicon	0.50 max.	0.50 max.	0.09
Cobalt	10.00-12.00	10.00-12.00	11.20
Manganese	0.10 max.	0.50 max.	0.02
Titanium	3.00-3.30	3.00-3.30	3.07
Molybdenum	9.00-10.50	9.00-10.50	10.02
Aluminum	1.40-1.60	1.50-1.80	1.41
Boron	0.003-0.010	0.003 max.	0.006
Nickel	Balance	Balance	Balance
Sulphur	0.015 max.	-	0.008

* From Haynes Stellite Company, Haynes Alloy No. R-41 No. F-30, 155.

TABLE 2

Mechanical Properties of R-41 (As-Received)*

0.020" Sheet, Haynes Stellite Co., Heat TV-592

Test Temp.	Direction	F_{ty} ksi	F_{tu} ksi	e %	Notched T.S. (K_t=6.3) ksi	Notched/Unnotched Tensile Ratio
+78°F	Long.	70.0	133	49	107	
	"	72.5	135	47	105	
	"	73.3	134	47	110	
	Average	71.9	134	48	107	0.80
+78°F	Trans.	61.8	133	44	111	
	"	61.8	133	46	111	
	Average	61.8	133	45	111	0.83
-100°F	Long.	83.4	151	51	121	
	"	85.1	151	52	121	
	Average	84.3	151	52	121	0.80
-100°F	Trans.	112	151	49	120	
	"	83.4	148	50	117	
	"	78.7	153	49		
	Average	91.4	151	49	119	0.79
-320°F	Long.	101	179	52	140	
	"	93.2	178	50	140	
	"	88.2	177	50		
	Average	94.1	178	51	140	0.79
-320°F	Trans.	89.6	177	47	142	
	"	93.7	175	47	143	
	Average	91.7	176	47	143	0.81

TABLE 2 (Cont.)

Test Temp.	Direction	F_{ty} ksi	F_{tu} ksi	e %	Notched T.S. (K_t=6.3) ksi	Notched/Unnotched Tensile Ratio
-423°F	Long.	119	222	48	169	
	"	125	234	50	132	
	"	135	212	35	136	
	Average	126	223	44	146	0.65
-423°F	Trans.	113	192	43	169	
	"	107	202	45	203	
	Average	110	197	44	186	0.94

* Solution treated at 1975°F, rapid quench

TABLE 3

Mechanical Properties of R-41 (Age Hardened)*

0.020" Sheet, Haynes Stellite Co., Heat TV-592

Test Temp.	Direction	F_{ty} ksi	F_{tu} ksi	e %	Notched T.S. (K_t=6.3) ksi	Notched/Unnotched Tensile Ratio
+78°F	Long.	-	177	14	162	
	"	138	184	21	167	
	"	138	183	20	163	
	Average	138	181	18	164	0.91
+78°F	Trans.	134	172	10	164	
	"	134	176	14	162	
	Average	134	174	12	163	0.94
-100°F	Long.	-	192	13	173	
	"	148	192	13	173	
	Average	148	192	13	173	0.90
-100°F	Trans.	145	179	9	174	
	"	145	182	9	176	
	"	145	187	11		
	Average	145	183	10	175	0.96
-320°F	Long.	162	203	9	188	
	"	161	199	9	190	
	"	160	203	10		
	Average	161	202	9	189	0.94
-320°F	Trans.	162	196	7	189	
	"	162	196	7	182	
	Average	162	196	7	189	
					187	0.95

TABLE 3 (Cont.)

Test Temp.	Direction	F_{ty} ksi	F_{tu} ksi	* %	Notched T.S. (K_t=6.3) ksi	Notched/Unnotched Tensile Ratio
-423°F	Long.	182	202	6	207	
	"	178	215	7	215	
	"	178	219	6	206	
	Average	179	212	6	209	0.99
-423°F	Trans.	177	206	5	190	
	"	170	205	5	219	
	Average	174	206	5	205	1.00

* Solution treated and aged for 30 min. at 1950°F air cool, plus 16 hours at 1400°F air cool.

TABLE 4

Available Forms of R-41 Alloy*

Sheet	Thickness: 0.020 in. to 0.1875 in. Maximum size: 48 in x 144 in. Usual rolling size: 36 in. x 96 in. Also available upon request: Thickness of 0.010 in. to 0.0199 in. As-cold-reduced, bright finish sheet Unless otherwise specified sheet will be furnished in the solution treated condition.
Plate	Thickness: 3/16 in. to 2 in. inclusive. Maximum width: 48 in. Maximum length: 132 in. Maximum weight: 800 lb.
Bar	Nominal diameter: ½ in. to 2 in. - maximum mill length: 10 ft. Nominal diameter: 2 in. to 3½ in.-Maximum mill length: 8 ft.
Wire	Nominal diameters: 1/16 in. to ¼ in.
Forging Stock	Maximum billet diameter: 8 in. Shape: Tuned and ground rounds.
Investment Castings	

* From Haynes Stellite Company, Haynes Alloy No. R-41 No. F-30, 155

Appendix A

References to Publications on R-41*

1. , Haynes Alloy No. R-41, Bulletin No. F-30, 155. Haynes Stellite Company, Division of Union Carbide Corporation.

2. , Rene' 41, Vacuum Melted Alloy, Bulletin No. VM-107, Metallurgical Products Department, General Electric Company, May 1958.

3. G. Sachs and R. Ford Pray II, Air Weapons Materials Application Handbook Metals and Alloys, ARDC TR59-66 under USAF Contract No. AF18(600)-1794, 1st Edition, Syracuse University Research Institute, Dunbar, 1959.

4. A. Giuntoli, Short-Time Elevated Temperature Mechanical Properties of R-235, D-979, Rene'41, and Unitemp 212 High Temperature Alloys, Report No. MP 58-337, Materials & Processes Laboratory, Convair, San Diego, A Division of General Dynamics Corporation, February, 1959.

5. , Rene'41, One of the Strongest Materials Available for Use in the Temperature Range 1200°F-1800°F, Series No. 86, Cannon-Muskegon Corporation.

6. , Comparative Properties Data on Some High Temperature Alloys, Investment Cast and Wrought, Haynes Stellite Company, a Division of Union Carbide Corporation, March, 1959.

7. J. R. Kattus, Tensile and Creep Properties of Structural Alloys Under Conditions of Rapid Heating, Rapid Loading, and Short-Times at Temperature, 3962-867-2-I, Southern Research Institute, April, 1959.

* These publications are available in the Materials Research Group, 595-20

CONVAIR ASTRONAUTICS

REPORT MRG-189
PAGE 1
14 October 1960

SUBJECT: Mechanical Properties of Titanium and Titanium Alloys at Cryogenic Temperatures

ABSTRACT: This report includes the mechanical property data obtained in the Materials Research Group on titanium and titanium alloys at +78°F, -320°F and -423°F. The data include tensile strengths, 0.2% yield strengths, % elongation, notched tensile strengths, notched/unnotched tensile ratios and charpy impact values on base metal and welded joints (heliarc butt welds and fusion welds with filler metal added). Materials tested include 30% cold-rolled Ti-75A commercially pure titanium (AMS 4901) and the following titanium alloys: 5Al-2.5Sn, 5Al-5Zr-5Sn, 6Al-4Zr-IV, 7Al-12Zr, 8Al-2Cb-1Ta, 5Al-2.75Cr-1.25Fe, 6Al-4V and 13V-11Cr-3Al.

An analysis of the results is included for each alloy which primarily discusses the usefulness of the material for structural applications at cryogenic temperatures. Also, correlations of the materials's mechanical properties are made with its chemistry, impurity content, microstructure, primary working and heat treatment. Recommendations are made concerning the use of titanium and its alloys at cryogenic temperatures and future research work which has been suggested by this program.

Prepared by J. L. Christian
J. L. Christian

Approved by H. Hurlich
A. Hurlich
Research Group Engineer
Materials Research Group

AH:JLC:jfd

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SUBJECT: Mechanical Properties of Titanium and Titanium Alloys at Cryogenic Temperatures.

INTRODUCTION

Very low temperatures are encountered in current and proposed missiles and space vehicles due to the use of cryogenic propellants such as liquid oxygen and liquid hydrogen (boiling points of -297°F and -423°F respectively) and due to the near absolute zero temperatures encountered under certain conditions in outer space. Therefore, the properties of engineering materials at these extreme subzero temperatures are becoming of prime importance to the design engineer.

The primary purpose of this investigation was to determine the mechanical properties of cold-rolled commercially pure titanium and several titanium base alloys in order to evaluate their usefulness for structural applications at cryogenic temperatures. It was also the purpose of this program to correlate mechanical properties with such variables as chemistry, impurity content, microstructure, primary working and heat treatment in order to better understand the mode of deformation and fracture characteristics of titanium and its alloys as a function of temperature. Another purpose was to make definite recommendations for the future development of titanium alloys in order to improve their properties at cryogenic temperatures. The materials tested in this program include cold-rolled 75A commercially pure titanium (AMS 4901) and the following titanium alloys: 5Al-2.5Sn, 5Al-5Zr-5Sn, 6Al-4Zr-1V, 7Al-12Zr, 8Al-2Cb-1Ta, 5Al-2.75Cr-1.25Fe, 6Al-4V, and 13V-11Cr-3Al. These represent the all alpha, the alpha-beta, and the all beta type alloys of which several were tested in various tempers and in various forms (sheet, plate and forging stock).

Many investigations have been made on the low temperature properties of titanium alloys (Refs. 1,2,3,4); however, in addition to the determination of tensile and elastic properties as a function of temperature, notched tensile properties and notched/unnotched tensile ratios and Charpy impact values were determined. The notched/unnotched ratios were determined as a function of temperature in order to evaluate the toughness, which is often referred to in terms of resistance to brittle fracture, or notch sensitivity (Refs. 5, 6, 7). A notched specimen with a stress concentration factor (K_t) of 6.3 was selected for use in this investigation because previous axial fatigue tests of complex welded joints and fatigue and burst tests of pressure vessels made of 301 extra full hard stainless steel exhibited excellent correlation with notched/unnotched tensile ratios obtained with this value of K_t over a range of temperatures from 78° to -423°F (Ref. 8). Data were obtained on specimens with less acute notches (e.g., K_t of 2.5-3.0) and were found to be less discriminatory between tough and brittle materials; in fact notched/unnothced ratios

of near unity were obtained on some materials which were known to be brittle (Ref. 8). At the other extreme, however, stress concentration factors of 15 to 18 have been employed by some investigators (Ref. 4) and these tests in general tend to make all materials appear brittle. Thus, notched/unnotched tensile ratios using a K_t of 6.3 have proven to be both discriminatory between tough and brittle materials and to correlate with service behavior.

MATERIALS, TEST SPECIMENS AND APPARATUS

The titanium alloys used in this investigation and their history and chemical analyses are listed in Table 1. The tensile specimens used in this investigation are shown in Fig. 1 and 2. All tensile specimens were inspected and individually measured for area determination. Notched specimens were inspected and measured by means of an optical comparator, and all specimens out of tolerance were rejected. The stress concentration factor (K_t), as determined by $\sqrt{\frac{1/2 \text{ width between notches}}{\text{radius of the notch}}}$, was 6.3 with "in tolerance" limits of 5.7 to 7.1.

The testing apparatus consisted of a 50,000-lb. Baldwin universal testing machine equipped with a continuous stress-strain recorder and strain pacer. Standard extensometers were used at room temperature and a specially designed cryo-extensometer was used at low temperatures. Specially constructed cryostats were used for testing at sub-zero temperatures; a small open cryostat for -100° and -320°F, and a gas-tight cryostat insulated by a vacuum chamber, liquid nitrogen jacket and foamed polyurethane, for tensile testing at -423°F. A full description of the cryostat, cryo-extensometer, and accessory equipment, as well as the safety features and rapidity of testing can be found in Ref. 9. The tensile machine, extensometers and accessory equipment were periodically checked and calibrated.

EXPERIMENTAL PROCEDURE

Tensile tests were performed at 78°F (room temperature), -100°F by immersion in a bath of dry ice and alcohol, -320°F by immersion in liquid nitrogen and -423°F by immersion in liquid hydrogen. Tests were conducted after the specimens came to temperature as determined by a copper-constantan thermocouple taped to the test section. Times required to reach temperature were from 3 to 6 minutes after immersion. The smooth tensile specimens were tested at a strain rate of 0.001 in./in/minute to yield, followed by a rate of 0.15 in./minute until fracture. Notched tensile specimens were tested at 0.001 in./in./minute, as determined by extensometers, until fracture. Yield strengths were determined from the continuous stress-strain curves by the 0.2% offset method. Elongations reported herein are total elongations as determined by scribe marks on a surface dye and read at 10X magnification over a 2-in. gage length for flat tensile specimens and a 1-in. gage length for the round test bars. Hardness measurements were made on a Rockwell superficial tester on the 15-N scale at room temperature.

EXPERIMENTAL RESULTS

The mechanical properties (tensile strengths, .2% yield strengths and elongations) of 30% cold-rolled 75-A commercially pure titanium from +78°F to -423°F are reported in Table II. Tables III thru VI present the mechanical properties of four different heats of 5Al-2.5Sn titanium alloy (A-110AT) at 78, -100, -320 and -423°F. These tables include the tensile properties of heliarc butt welded joints as well as base metal and notched data. Tables VII thru XI report the mechanical property data obtained on 5Al-5Zr-5Sn, 6Al-4Zr-1V, 7Al-12Zr, 8Al-2Cb-1Ta, and 5Al-2.75Cr-1.25Fe titanium alloys. Tables XII thru XIX contain tensile and Charpy impact data on 6Al-4V alloy in the annealed, solution treated, and solution treated and aged conditions. Data on the all beta titanium alloy, 13V-11Cr-3Al (B-120VCA) are presented in Tables XX thru XXII.

DISCUSSION OF RESULTS

Since the behavior of titanium and its alloys at cryogenic temperatures is not subject to generalizations, each alloy will be discussed separately.

30% Cold-Rolled Ti-75A Commercially Pure Titanium

The mechanical properties of the base metal are reported in Table II. Of immediate interest is the fact that the room temperature tensile and yield strengths have been considerably increased by cold-rolling the material 30%. However, the fact that the notched tensile strengths and notched/unnotched tensile ratios sharply decline with reduction in testing temperature indicates that the material is not suitable for structural applications at cryogenic temperatures. It is felt that the low temperature embrittlement of this material is partly due to the high interstitial (C, O_2, N_2, H_2) and impurity content present as well as the cold-rolling. Further research on the low temperature mechanical properties of Ti-45A and Ti-55A (AMS 4900 and AMS 4902) commercially pure material in the annealed condition is being planned.

5Al-2.5Sn Titanium (A-110AT)

Tables III thru VI present the data obtained on base metal and weld joints of 5Al-2.5Sn titanium alloy from 78°F to -423°F. Four different heats of material have been tested all in the mill annealed condition with sheet thicknesses ranging from 0.020 to 0.063 inches.

It is significant to note that the notched/unnotched tensile ratios are quite high for all four heats down to -320°F. Also, the notched tensile strengths continue to increase to -320°F. However, the .027 and .063 inch sheet materials (Tables IV and VI) experience a decrease in notched tensile strengths and notched/unnotched tensile ratios from -320 to -423°F. This indicates some degree of embrittlement of these materials at -423°F. Notch tensile strengths of the .020 and .040 inch sheet materials (Tables III and V) continue

to increase down to -423°F and the notched/unnotched tensile ratios remain quite high (0.97 and 0.86). The reason for the partial embrittlement of the before material heats is felt to be due to their higher interstitial content (C, O_2, N_2, H_2), which also explains why their room temperature tensile and yield strengths are higher than for the low interstitial content heats.

Mechanical properties of heliarc butt welded joints (no post heat treatment or doublers attached) show nearly 100% weld joint tensile efficiency and appreciable ductility down to -423°F.

Repeated loading tests of large welded joints (38" long coupon 4" in width with transverse heliarc butt joint made with no filler metal added, and in as-welded condition) were run on the 0.020 inch sheet material (Table V) at +78, -320 and -423°F. The specimens were axially loaded to 90% of their typical yield strength at each temperature. More than 2000 cycles were obtained at room temperature (maximum stress of 100,000 psi) and at -320°F (stress level of 162,000 psi) without failure or indication of failure (cracking). 539 cycles were obtained at -423°F (stress level of 205,000 psi) without failure in the test section (specimen failed in end doubler due to the nature of the test equipment). These tests validate three important points. First, that 5Al-2.5Sn titanium alloy retains sufficient toughness for structural applications at -423°F. Secondly, that straight heliarc butt welds without post treatment or doublers is 100% efficient down to -423°F. And, third, that the very large increase in tensile and yield strengths (100% increase from +78 to -423°F) may be used to advantage in those structures which see maximum stress only while at low temperature.

Of the large number of titanium alloys tested, the 5Al-2.5Sn alloy is the only one being recommended at this time for structural use in liquid hydrogen (-423°F). It is possible that the annealed 6Al-4V-titanium alloy may possess good toughness at -423°F if the interstitial content were kept very low, lower than presently found in commercial heats. This point is being further investigated. The 5Al-2.5Sn titanium alloy is readily available in gauges 0.020 inches and thicker and an effort to produce 0.010 inch material by rolling rather than chemical milling is presently being made. Resistance spot or fusion welding of the 5Al-2.5Sn alloy to itself or to commercially pure titanium is considered excellent. Present CV-A production welding equipment used in the Atlas and Centaur programs is capable of resistance spot welding this alloy with no equipment changes required. Fusion welding may also be accomplished on present equipment with minor modifications, in particular, an increase in inert gas shielding. Corrosion resistance of the base metal and fusion welds is excellent. Also, the alloy is compatible with liquid oxygen, liquid hydrogen, and many storable propellants, such as pentaborane, hydrazine, UDMH and nitrogen tetroxide. Further information on the physical properties (thermal, elastic, etc.), formability, machineability, etc., are available in the Materials Research Group.

5Al-5Zr-5Sn Titanium Alloy

The mechanical properties of the base metal and heliarc butt welded joints of this alloy are presented in Table VII. Notched tensile strengths and notched/unnotched tensile ratios indicate sufficient toughness to -320°F but partial embrittlement at -423°F. Welded joints were nearly 100% efficient at all testing temperatures. The microstructure of this alloy showed a small amount of beta phase present which may account for the embrittlement at -423°F, although recent information indicates that the zirconium alloying may be responsible for the low temperature embrittlement.

6Al-4Zr-1V Titanium Alloy

Table VIII presents the mechanical properties of this alloy. This material exhibits embrittlement at -320 and at -423°F as determined by notched tensile testing. The substantial amount of beta present in the microstructure and the combination of zirconium and vanadium is probably the cause for low temperature embrittlement.

7Al-12Zr Titanium Alloy

As may be seen in Table IX, this alloy also experiences some embrittlement at -320 and -423°F. The zirconium alloying content is felt to be much too high for cryogenic applications. Note in Table I that the interstitial content (C, O_2, N_2, H_2) of this material is quite low, which is further evidence that high zirconium contents in titanium cause low temperature embrittlement.

8Al-2Cb-1Ta Titanium Alloy

This alloy retains sufficient toughness for structural applications to -320°F but experiences some embrittlement at -423°F (see Table X). The tensile and yield strength of this alloy is 15-20% higher than for the low interstitial 5Al-2.5Sn alloy, therefore there is interest in further development of this material. As may be seen in Table I, the interstitial content of this material is very low; however it is felt that a small change in the alloying contents of this material may show improved toughness at -423°F. Another alloy, 8Al-1Mo-1V, is presently being evaluated for low temperature use.

5Al-2.75Cr-1.25Fe Titanium Alloy (RS-140)

Tensile properties and Charpy impact values of annealed and heat treated material are presented in Table XI. It is felt that further testing is required to fully evaluate this alloy, however Charpy impact values indicate an appreciable decrease in toughness of the annealed material with reduction in testing temperature.

6Al-4V-Titanium Alloy

Mechanical property data on this alloy are presented in Tables XII thru XIX. Data have been obtained on this alloy in the mill annealed, in the solution

treated and in the solution treated and aged conditions. Typical properties of four heats of annealed 6Al-4V are given in Tables XII thru XV. Notched tensile data and notched/unnotched tensile ratios indicate good toughness to -320°F with partial embrittlement at -423°F. Titanium Metals Corporation of America has arranged to provide CV-A with high purity samples of annealed 6Al-4V-Ti alloy sheet having very low interstitial contents to determine if the moderately high O_2 content of commerical quality 6Al-4V-Ti alloy is responsible for the embrittlement observed at -423°F.

Heliarc butt welds are nearly 100% efficient at all testing temperatures. Data on the solution treated alloy are given in Table XVI. Notched tensile data indicate a higher degree of embrittlement at cryogenic temperatures than observed in the annealed condition. Tables XVII and XVIII present data on solution quenched and aged 6Al-4V titanium alloy. Test specimens were prepared from the 24 "O.D." spherical storage bottles used for helium pressurization in the Atlas ICBM pneumatics system. Both notched tensile data and Charpy impact values indicate this alloy retains sufficient toughness for structural use at -320°F. Table XIX presents information obtained on 6Al-4V fusion welds using three different filler metals (6Al-4V, 3.5Al-2.5V, and 75A commercially pure titanium) and tested in the stress relieved and heat treated conditions. Tensile data and Charpy impact values are reported. Choice of filler metal would be dependent upon application.

13V-11Cr-3Al Titanium Alloy (B 120 VCA)

This is an all-beta type titanium alloy known for its high strength/density ratio at room temperature after aging. Tables XX thru XXII present data on both solution annealed and solution annealed and aged material at room and cryogenic temperatures. Notched tensile data and Charpy impact values indicate that the material is very brittle at -320°F, therefore this alloy is not recommended for structural applications at extreme sub-zero temperatures.

RECOMMENDATIONS

Based upon present information the following recommendations are made concerning the use of titanium alloys for structural applications at cryogenic temperatures. The only titanium alloy which is recommended at this time for use at liquid hydrogen temperatures is the 5Al-2.5Sn alloy. However, careful control over interstitial content is required to insure adequate toughness at -423°F. Several titanium alloys may be employed for structural use as low as -320°F. These include 6Al-4V (both annealed and heat treated), 8Al-2Cb-1Ta and 5Al-5Zr-5Sn titanium alloys (annealed condition). Again it is pointed out that low interstitial levels are required in all the titanium alloys as well as commercially pure titanium in order to achieve maximum toughness at sub-zero temperatures.

It is apparent from the data obtained in this program that several metallurgical factors affect the low temperature brittle fracture characteristics of titanium and its alloys. Of primary importance are microstructure chemistry, and impurity (including interstitials) content of the material. There is some

evidence that certain alloying elements (such as zirconium) adversely affect the low temperature toughness of titanium alloys. Also, it is quite apparent from this investigation as well as several other studies that high interstitials and certain impurities promote brittle fracture in titanium and its alloys. Alloys having an all-beta microstructure are brittle at reduced temperatures. A study of photomicrographs obtained on fractured surfaces of tensile specimens indicated that those materials with fine grained equiaxed structure (either alpha or alpha-beta) retained greater toughness at cryogenic temperatures than those materials with a course grained transformed structure (e.g. the solution treated 6Al-4V and 13V-11Cr-3Al alloys). The poor toughness of the cold-rolled 75A commercially pure titanium seems to indicate that cold-rolling may have a deleterious effect on the fracture properties of titanium at sub-zero temperatures.

It is recommended that further research be conducted, particularly in the field of alloy development, to produce high strength titanium alloys for structural use at cryogenic temperatures.

CONCLUSIONS

1. The 5Al-2.5Sn titanium alloy retains sufficient toughness in both base metal and weld joints for structural application down to liquid hydrogen temperatures (-423°F) provided that careful control over interstitial content is maintained. The large increase in tensile and yield strength of the 5Al-2.5 Sn alloy with reduction in temperature may be used to advantage in missile structures when maximum stress occurs while the material is subjected to sub-zero temperatures, such that low temperature design allowables can be used.

2. The following titanium alloys may be used for structural applications as low as -320°F but not at -423°F: 6Al-4V (both annealed and solution quenched and aged), 8Al-2Cb-1Ta, and 5Al-5Zr-5Sn.

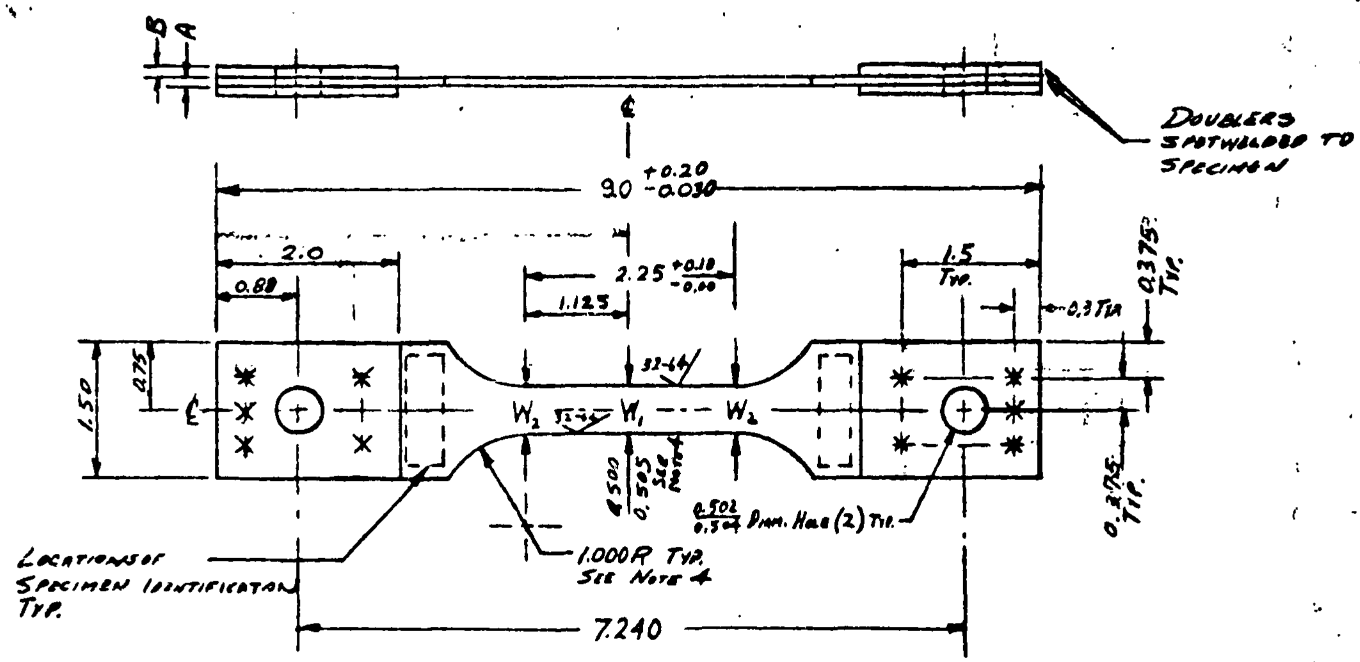
3. The 13V-11Cr-3Al titanium alloy offers a high strength/density material at room temperature but is not recommended for sub-zero applications because of excessive embrittlement at low temperatures.

4. Several metallurgical factors affect the fracture characteristics of titanium and its alloys at cryogenic temperatures. High interstitial contents adversely affects the toughness at cryogenic temperatures as well as certain alloying elements (e.g. zirconium). Greater toughness is obtained on materials with fine grained equiaxed microstructures than with coarse grained transformed microstructures. Cold-rolling has a deleterious effect on low temperature toughness.

5. Further research should be conducted, particularly in the area of alloy development, to provide more titanium alloys with improved strength and toughness for structural applications at cryogenic temperatures.

REVISIONS

EFF ON	INCORP	SYM	DESCRIPTION	DATE	APPROVAL



	SPECIMEN THICKNESS, A	DOUBLER THICKNESS, B	SPECIMEN MATERIAL	DOUBLER MATERIAL
	UP TO 0.030	0.025		

SEE NOTES ON SHEET 2 OF 2

UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES
TOLERANCES ON

.XX	.XXX	ANGLES
±0.03	±0.010	±0°30'

ALL MACHINE SURFACES 64-125 UNLESS OTHERWISE SPECIFIED

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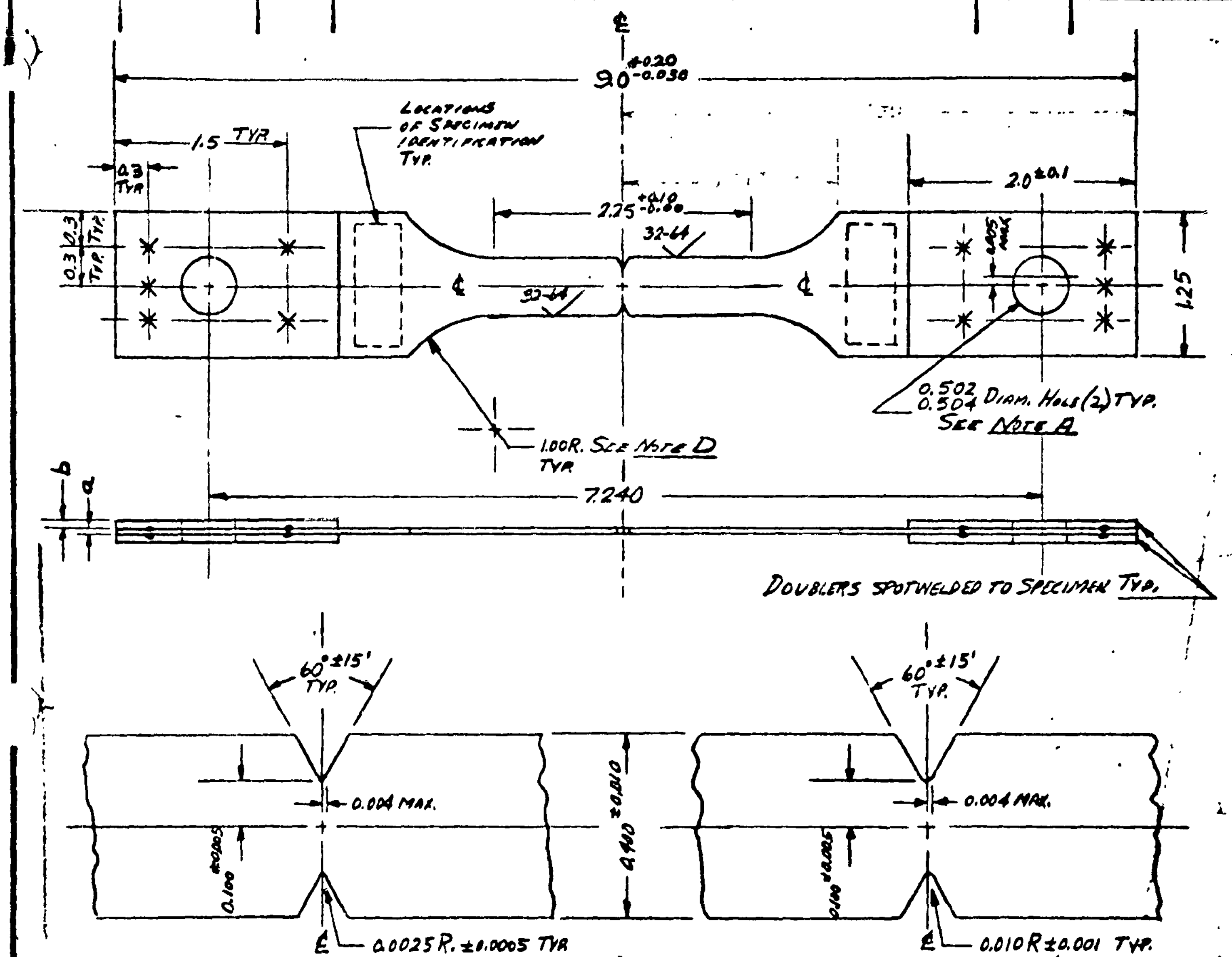
SHEET 1 OF 2

DWG A SIZE

FLAT TENSILE SPECIMEN (STANDARD)

REVISIONS

EFF ON	INCORP	SYM	DESCRIPTION	DATE	APPROVAL



TYPE "A" NOTCH – $\frac{A}{R}$ = 40 (32-52)
SEE NOTES B & C

TYPE "B" NOTCH – $\frac{A}{R}$ = 10 (8.6-11.1)
SEE NOTES B & C

SEE NOTES ON SHEET 2 OF 2

SPECIMEN THICKNESS, a	DOUBLER THICKNESS, b	SPECIMEN MATERIAL	DOUBLER MATERIAL
UP TO 0.030	0.025		

Figure 2a

UNLESS OTHERWISE SPECIFIED
DIMENSIONS IN INCHES
TOLERANCES ON .XX ±0.03, .XXX ±0.010, ANGLES ±0°30'

ALL MACHINE SURFACES 64-125 UNLESS OTHERWISE SPECIFIED

CKD	L. GIRTON	9/10/59
STD		
GRP	MAT'L RESEARCH	545-2
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SHEET 1 OF 2
DWG A SIZE

NOTCHED TENSILE SPECIMEN

TABLE I

History and Chemical Analysis of Tita

TABLE	MATERIAL	TEMPER	THICKNESS (IN.)	HARDNESS 15-N SUPERFICIAL	HEAT NO.	PRODUCER
II	75A (Commercially)	30% Cold Rolled	0.012	74	M-9656	TMCA
III	5Al-2.5 Sn	Annealed	0.040	78	M-8465	TMCA
IV	5Al-2.5 Sn	Annealed	0.027	78	M-9048	TMCA
V	5Al-2.5 Sn	Annealed	0.020	78	31387	Reactive Metals
VI	5Al-2.5 Sn	Annealed	0.063	80	D-2073	
VII	5Al-5Zr-5Sn	Annealed	0.062	76	V-1464	TMCA
VIII	6Al-4Zr-1V	Annealed	0.090	80	V-1166	TMCA
IX	7Al-12Zr	Annealed	0.050	80	R-98321	Crucible
X	8Al-2Cb-1Ta	Annealed	0.026	79	23732	Reactive Metals
XI	5Al-2.75Cr-1.25 Fe	Given in Table XI			R-11730	Crucible
XII	6Al-4V	Annealed	0.090	74	M-8619	TMCA
XIII	6Al-4V	Annealed	0.063	76	M-8907	TMCA
XIV	6Al-4V	Annealed	0.063	78	B-23132	-
XV	6Al-4V	Annealed	0.063	76	M-23262	-
XVI	6Al-4V	Solution Treated	0.020	80	—	-
XX	13V-11Cr-3Al	Solution Annealed	0.062	75	—	Crucible
XXI	13V-11Cr-3Al	Solution Treated and Aged	0.062	80	—	Crucible
XXII	13V-11Cr-3Al	Given Table XXII	0.250		R-98103	Crucible

Al
5.8
5.4
4.9
4.8
5.8
7.0
7.67
4.90
5.8
6.1
6.21
5.92
3.2
3.2
5.3

1

TABLE I

Analysis of Titanium Base Alloys

CER	Al	Cb	Cr	Fe	Sn	Ta	V	Zr	C	H_2	N_2	O_2
								CHEMISTRY				
	5.8			0.09	2.4				0.017	0.0108	0.010	0.103
	5.4			0.21	2.5				0.021	0.015	0.010	
ve												
	4.9				2.4				0.03	0.0061	0.03	
	4.8			0.045	4.7			4.8	0.02	0.005	0.014	0.06
	5.8						0.087	3.6	0.020	84ppm	0.024	
le	7.0							11.5	0.01	0.012	0.01	0.09
ve	7.67	1.89		0.19		0.96			0.02	135ppm		0.001
le	4.90		2.70	1.05					0.031		0.010	
	5.8			0.09			4.1		0.028	0.005	0.008	
	6.1			0.09			3.9		0.028	0.0049	0.022	0.11
	6.21			0.16			3.81		0.007	0.0118	0.010	
	5.92			0.41			4.06		0.016	0.0435	0.013	
le	3.2		10.6				13.3		0.03	212ppm	0.01	
le	3.2		10.6				13.3		0.03	212ppm	0.01	
le	5.3		9.9				12.5		0.03	0.0184	0.02	

2

TABLE II

Mechanical Properties of Titanium, 75-A Commercially Pure

0.012" Sheet, TMCA, Heat M-9656, 30% Cold Rolled

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	el. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.	121	138	5	149	
	Long.	121	136	5	141	
	Ave.	121	137	5	145	1.06
+78°F	Trans.	122	145	5	165	
	Trans.	122	147	5	163	
	Ave.	122	146	5	164	1.12
-60°F	Long.	-	154	-	145	
	Long.				147	
	Ave.	-	154	-	146	0.95
-60°F	Trans.	-	171	-	117	
	Trans.	-	172	-		
	Ave.	-	172	-	117	0.68
-320°F	Long.	-	211	5	151	
	Long.	-	212	5	155	
	Ave.	-	212	5	153	0.72
-320°F	Trans.	-	210	3	122	
	Trans.	-	212	3	137	
	Ave.	-	211	3	130	0.62
-423°F	Long.	217	233	1	128	
	Long.	-	241	1	130	
	Long.		228		122	
	Ave.	217	234	1	127	0.54
-423°F	Trans.	-	237	1	121	
	Trans.	-	241	1	125	
	Trans.				102	
	Ave.	-	239	1	116	0.49

TABLE III

Mechanical Properties of Titanium 5Al-2.5 Sn Alloy

0.040" Sheet, TMCA, Heat M-8465, Mill Annealed

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	el. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/ UNNOTCHED TENSILE RATIO	HELIARC BUTT WELD T.S., ksi	WELD EL %	JOINT EFF %
+78°F	Long.	113	118	19	154		122	11	
	Long.	111	118	19	153		121	13	
	Long.	114	117	19	162		120	13	
	Long.	113	119	19	163				
	Long.	111	119	19					
	Ave.	113	118	19	158	1.34	121	12	100
+78°F	Trans.	114	120	14	159				
	Trans.	115	120	13					
	Ave.	115	120	14	159	1.33			
-100°F	Long.	134	140	17	174		141	10	
	Long.	136	144	20	174		142	12	
	Long.	135	143	19	176				
	Ave.	135	142	18	175	1.23	142	11	100
-100°F	Trans.	137	144	11					
	Trans.	137	143	11					
	Ave.	137	144	11					
-320°F	Long.	184	197	11	224		190	2	
	Long.	185	196	18	[illegible]		193	11	
	Long.	182	195	18	222		194	11	
	Long.	184	191	15	229				
	Long.	186	197	16					
	Ave.	184	196	15	226	1.15	192	8	98
-320°F	Trans.	186	197	11	219				
	Trans.	184	200	11	221				
	Ave.	185	199	11	220	1.11			
-423°F	Long.	227	248	14	235		234	3	
	Long.	237	246	14	244		225	0	
	Long.	226	244	-	232		240	8	
	Long.	225	248	15	221				
	Long.	234	251	15	234				
	Ave.	230	247	15	239	0.97	233	4	94
-423°F	Trans.	-	243	9	202				
	Trans.	-	244	10	213				
	Trans.	225	248	15					
	Trans.	234	251	-					
	Ave.	230	244	11	208	0.85			

TABLE IV

Mechanical Properties of Titanium 5Al-2.5Sn

0.027" Sheet, TMCA, Heat M-9048, Mill Annealed

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	el. %	NOTCHED T.S. (Kt=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.	123	133	15	178	
	Long.	123	133	15		
	Long.	123	133	16	—	
	Ave.	123	133	15	178	1.34
+78°F	Trans.	124	131	14	176	
	Trans.	124	133	14	177	
	Ave.	124	132	14	177	1.34
-100°F	Long.	141	159	15	195	
	Long.	148	160	15		
	Long.	149	161	15	—	
	Ave.	146	160	15	195	1.22
-100°F	Trans.	146	156	14	189	
	Trans.	148	157	14	190	
	Ave.	147	157	14	190	1.21
-320°F	Long.	195	210	17	247	
	Long.	195	209	17		
	Long.	194	210	16	—	
	Ave.	195	210	17	247	1.18
-320°F	Trans.	191	207	13	235	
	Trans.	204	216	15	241	
	Trans.	—	—	—	238	
	Ave.	198	212	14	238	1.12
-423°F	Long.	236	259	9	223	
	Long.	244	259	12	194	
	Long.	234	259	5	—	
	Ave.	238	259	9	209	0.81
-423°F	Trans.	232	255	7	216	
	Trans.	230	254	9	211	
	Trans.	—	—	—	213	
	Ave.	231	255	8	213	0.84

TABLE V

Mechanical Properties of Titanium 5Al-2.5 Sn

0.020" Sheet, Reactive Metals, Heat 31387, Mill Annealed

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	el. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/ UNNOTCHED TENSILE RATIO	HELIARC BUTT WELD T.S., ksi	WELD EL %	JOINT EFF %
+78°F	Long.	111	122	12	154		118	7	
	Long.	111	123	12	147		124	10	
	Long.						122	9	
	Ave.	111	123	12	151	1.23	121	9	98
-423°F	Long.	230	245	5	227		252	2	
	Long.	247	260	3	207		299	1	
	Long.						249	2	
	Ave.	239	253	4	217	0.86	267	2	100

TABLE VI

Mechanical Properties of Titanium 5Al-2.5 Sn Alloy

0.063" Sheet, Crucible, Heat D-2073, Mill Annealed

TEST TEMP.	DIRECTION		F_{ty} ksi	F_{tu} ksi	el. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long		122	130	17	174	
	Long.		122	129	17	174	
		Ave.	122	130	17	174	1.34
+78°F	Trans.					175	
-100°F	Long.		146	153	17	202	
	Long.					200	
		Ave.	146	153	17	201	1.31
-320°F	Long.		201	212	13	248	
	Long.		205	216	13	244	
		Ave.	203	214	13	246	1.15
-423°F	Long.		257	262	2	181	
	Long.		258	264	-	179	
	Long.					197	
		Ave.	258	263	2	186	0.71
-423°F	Trans.					164	

TABLE VII

Mechanical Properties of Titanium 5Al-5Zr-5 Sn Alloy

0.062" Sheet, TMCA, Heat V-1464, Mill Annealed

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	el. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/ UNNOTCHED TENSILE RATIO	HELIARC BUTT WELD T.S., ksi	WELD EL %	JOINT EFF. %
+78°F	Long.	120	125	18	155		126	17	
	Long.	120	127	17	155		126	10	
	Long.	122	126	17	155		127	15	
	Ave.	121	126	17	155	1.23	126	14	100
+78°F	Trans.	120	123	17	155				
	Trans.	120	123	17	156				
	Ave.	120	123	17	156	1.27			
-100°F	Long.	146	151	17	181		151	7	
	Long.	145	150	17	182		151	16	
	Long.	144	150	18	181		151	16	
	Ave.	145	150	17	181	1.21	151	13	100
-100°F	Trans.	143	149	16	181				
	Trans.	143	148	17	180				
	Ave.	143	149	17	181	1.21			
-320°F	Long.	192	209	16	204		207	5	
	Long.	192	209	17	190		209	7	
	Long.	193	208	17	202		210	9	
	Ave.	192	209	17	199	0.95	209	7	100
-320°F	Trans.	188	204	15	185				
	Trans.	186	203	15	191				
	Ave.	187	204	15	188	0.92			
-423°F	Long	230	254	11	181		242	2	
	Long.	239	265	11	178		242	3	
	Long.	236	268	11	189		242	2	
	Ave.	235	262	11	183	0.70	242	2	92
-423°F	Trans.	225	256	10	161				
	Trans.	216	251	8	165				
	Ave.	221	254	9	163	0.64			

TABLE VIII

Mechanical Properties of Titanium 6Al-4Zr-1V Alloy

0.090" Sheet, TMCA, Heat V-1166, Mill Annealed

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	el. %	NOTCHED T.S. (K_t=6.3)	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.	137	142	16	173	
	Long.	136	141	16	173	
	Ave.	137	142	16	173	1.22
+78°F	Trans.	137	139	16	173	
	Trans.	136	139	16	173	
	Ave.	137	139	16	173	1.24
-100°F	Long.	160	167	15	197	
	Long.	159	167	15	197	
	Long.				195	
	Ave.	160	167	15	196	1.17
-320°F	Long.	-	227	9	186	
	Long.	207	228	12	184	
	Long.	216	227	10		
	Ave.	212	227	10	185	0.81
-320°F	Trans.	218	226	12	169	
	Trans.				172	
	Ave.	218	226	12	171	0.76
-423°F	Long.	266	279	5	151	
	Long.	261	279	5	149	
	Ave.	264	279	5	150	0.54
-423°F	Trans.	264	277	4	157	
	Trans.				152	
	Ave.	264	277	0	155	0.56

TABLE IX

Mechanical Properties of Titanium 7Al-12Zr Alloy

0.050" Sheet, Crucible, Heat R-98321, Mill Annealed 1650°F, 1 Hr.

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	el. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.	134	146	11	179	
	Long.	133	142	11	179	
	Long.	132	141	10	176	
	Ave.	133	143	11	178	1.24
+78°F	Trans.	133	139	16	179	
	Trans.	132	138	12	180	
	Ave.	133	139	14	180	1.29
-100°F	Long.	148	159	10	155	
	Long.	146	157	12	-	
	Ave.	147	158	11	155	0.98
-100°F	Trans.	149	158	11	193	
	Trans.	148	158	11	198	
	Trans.	150	158	11		
	Ave.	149	158	11	196	1.24
-320°F	Long.	197	214	11	173	
	Long.	196	214	13	162	
	Ave.	197	214	12	168	0.79
-320°F	Trans.	194	209	16	190	
	Trans.	195	212	12	196	
	Trans.	194	212	14		
	Ave.	194	211	14	193	0.91
-423°F	Long.	241	252	7	131	
	Long.	239	251	5	150	
	Long.	239	249	-		
	Ave.	240	251	6	141	0.56
-423°F	Trans.	239	251	4	161	
	Trans.	230	247	5	151	
	Ave.	235	249	5	156	0.63

TABLE X

Mechanical Properties of Titanium 8Al-2Cb-1Ta Alloy

0.026" Sheet, Reactive Metals, Heat No. 23732, Mill Annealed

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	el. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.	131	141	12	172	
	Long.	130	143	12	175	
	Long.	132	143	12	160	
	Ave.	131	142	12	169	1.19
+78°F	Trans.	129	143	14	169	
	Trans.	129	137	14	166	
	Ave.	129	140	14	168	1.20
-100°F	Long	156	165	13	196	
	Long.	156	165	13	198	
	Long.	155	165	12	199	
	Ave.	156	165	13	198	1.20
-100°F	Trans.	151	161	9	191	
	Trans.				191	
	Ave.	151	161	9	191	1.19
-320°F	Long.	195	207	13	240	
	Long.	204	221	12	248	
	Long.	214	223	13	245	
	Ave.	204	217	13	244	1.12
-320°F	Trans.	—	—	—	204	
	Ave.				204	
-423°F	Long.	252	266	0	207	
	Long.	248	264	1	243	
	Long.				230	
	Ave.	250	265	1	227	0.86
-423°F	Trans.	215	248	0	158	
	Trans.	-	278	1	201	
	Ave.	215	263	1	180	0.68

TABLE XI

Mechanical Properties of Titanium 5AL-2.75 Cr-1.25 Fe, Alloy

0.250" Plate, Crucible, Heat R-11730

CONDITION	TEST TEMP.	YIELD STRENGTH 0.02% OFFSET psi	TENSILE STRENGTH psi (1)	% ELONG	% R.A.	V-NOTCH CHARPY IMPACT FT. LBS. (2)
Annealed 1425°F, 1 hr. air cooled	+70°F	147,300 (3)	157,900	15.9	43.6	27.5 (4)
	-320°F	234,700 (4)	244,100	13.1	18.8	7.7 (4)
Heat Treated, 1450°F 1 hr. water quenched, 900°F, 6 hrs. air cool	+70°F	163,500 (4)	184,000	7.7	13.3	4.0 (4)
	-320°F	256,000 (4)	269,900	2.2	4.0	3.4 (4)

(1) Tensile test specimens were 0.113" diameter round shank, with 0.45" gage length.

(2) V-Notch Charpy impact specimens were twice standard width (0.788"), 1/2 standard thickness (0.197"), and 1/2 standard notch depth (0.039"), but with standard notch contour.

(3) Average of 5 tests; longitudinal to grain direction.

(4) Average of 2 tests; longitudinal to grain direction.

TABLE XII

Mechanical Properties of Titanium 6Al-4V Alloy

0.090" Sheet, TMCA, Heat M-8619, Mill Annealed

TEST TEMP.	DIRECTION		F_{ty} ksi	F_{tu} ksi	el. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.		127	137	13	[illegible]	
	Long.		127	136	13	162	
	Long.		128	136	13	161	
		Ave.	127	136	13	162	1.19
+78°F	Trans.		128	136	13	168	
	Trans.		128	135	13	168	
		Ave.	128	136	13	168	1.24
-320°F	Long.		209	215	12	231	
	Long.		210	215	12	231	
	Long.		209	216	13	236	
		Ave.	209	215	12	233	1.08
-320°F	Trans.		210	214	12	246	
	Trans.		210	214	13		
		Ave.	210	214	13	246	1.15
-423oF	Long.		260	260	2	163	
	Long.		259	259	2	162	
	Long.		260	260	2	161	
		Ave.	260	260	2	162	0.62
-423°F	Trans.		244	262	4	168	
	Trans.		251	258	2	168	
		Ave.	248	260	3	168	0.65

TABLE XIII

Mechanical Properties of Titanium 6Al-4V Alloy

0.063" Sheet, TMCA, Heat M-8907, Mill Annealed

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	el. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/ UNNOTCHED TENSILE RATIO	HELIARC BUTT WELD T.S., ksi	WELD EL %	JOINT EFF %
+78°F	Long.	128	141	11	157		142	10	
	Long.	130	141	12	156		142	10	
	Long.	129	140	11			142	10	
	Ave.	129	141	11	157	1.11	142	10	100
+78°F	Trans.	135	145	13	169				
	Trans.	137	146	12	169				
	Ave.	136	146	13	169	1.16			
-100°F	Long.	157	166	9	170		168	9	
	Long.	158	166	12	164		168	10	
	Long.						169	10	
	Ave.	158	166	11	167	1.01	168	10	100
-100°F	Trans.	161	168	10	186				
	Trans.	160	169	11	183				
	Ave.	161	169	11	185	1.09			
-320°F	Long.	212	220	11	200		221	8	
	Long.	211	219	11	181		221	11	
	Long.	210	217	8			221	12	
	Ave.	211	219	10	191	0.87	221	10	100
-320°F	Trans.	213	218	8	182				
	Trans.	217	222	11	191				
	Trans.	214	218	11					
	Ave.	215	219	10	187	0.85			
-423°F	Long.	249	258	-	185		270	5	
	Long.	248	256	2	181		292	3	
	Long.	239	249	2			263	3	
	Ave.	245	253	2	183	0.72	275	4	100
-423°	Trans.	245	254	2	182				
	Trans.	251	261	2	191				
	Trans.	-	250	1					
	Ave.	248	255	2	187	0.73			

TABLE XIV

Mechanical Properties of Titanium 6Al-4V Alloy

0.063" Sheet, Heat B-23132, Mill Annealed

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	el. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.	121	133	10	151	
	Long.	121	134	11	149	
	Ave.	121	134	11	150	1.12
+78°F	Trans.	137	145	10	167	
	Trans.	138	145	11	167	
	Ave.	138	145	11	167	1.15
-320°F	Long.	208	217	10		
	Long.					
	Long.					
	Ave.	—	—	—		
-423°F	Long.	262	269	2	185	
	Long.	263	273	2	179	
	Long.					
	Ave.	263	271	2	182	0.67
-423°F	Trans.	242	255	2	177	
	Trans.	242	255	2	172	
	Ave.	242	255	2	175	0.69

TABEL XV

Mechanical Properties of Titanium 6Al-4V Alloy

0.063" Sheet, Heat M-23262, Mill Annealed

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	el. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.	98	137	11	154	
	Long.	104	141	12	144	
	Long.	115	145	9	148	
	Ave.	106	141	11	149	1.06
+78°F	Trans.	127	157	8	168	
	Trans.	127	157	8	167	
	Ave.	127	157	8	168	1.07
-100°F	Long.	125	171	11	162	
	Long.	123	171	11	154	
	Long.	122	171	11	161	
	Ave.	123	171	11	159	0.93
-100°F	Trans.	145	177	6	174	
	Trans.	144	171	-	171	
	Ave.	145	174	6	173	0.99
-320°F	Long.	177	223	11	193	
	Long.	166	215	8	200	
	Long.	177	219	7	193	
	Ave.	173	219	9	195	0,89
-320°F	Trans.	198	215	3	191	
	Trans.	195	217	5	184	
	Ave.	197	216	4	188	0.87
-423°F	Long.	227	256	2	174	
	Long.	230	248	0	173	
	Long.	203	236	2	182	
	Ave.	220	247	1	176	
-423°F	Trans.	227	254	7	162	
	Trans.	-	231	0	161	
	Ave.	227	243	4	162	0.67

TABLE XVI

Mechanical Properties of Titanium 6Al-4V Alloy

0.020" Sheet, Solution Treated (1725°F, 30 Min., WQ)

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	el. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.	130	160	7	170	
	Long.	130	159	8	182	
	Long.	128	156	8	182	
	Ave	129	158	8	178	1.13
+78°F	Trans.	126	157	10	180	
	Trans.	128	160	11	170	
	Ave	127	159	11	175	1.10
-100°F	Long.	154	195	9	187	
	Long.	148	187	11	190	
	Ave	151	191	10	189	0.99
-100°F	Trans.	145	189	12	179	
	Trans.	145	189	12		
	Ave	145	189	12	179	0.95
-320°F	Long.	-	246	7	190	
	Long.	207	239	5	198	
	Ave	207	243	6	194	0.80
-320°F	Trans.	207	244	11	179	
	Trans.	195	240	11	169	
	Ave	201	242	11	174	0.72
-423°F	Long.	224	259	0	152	
	Long.	236	-	-	152	
	Long.	234	259	0	169	
	Ave	231	259	0	158	0.61
-423°F	Trans.	228	277	2	110	
	Trans.	245	280	0	149	
	Ave	237	279	1	130	0.47

TABLE XVII

Mechanical Properties of Titanium 6Al-4V Alloy

1/2" to 3/4" Wall Thickness, Hemispherical Forgings, Heat Treated

TEST TEMP.	DIRECTION WITH RESPECT TO GRAIN FLOW	YIELD STRENGTH psi	TENSILE STRENGTH psi	% ELONG.	% R.A.	V-NOTCH CHARPY (5) ft. lbs.
+70°F	Long.	127,700 (1)	146,200	27.0	53.5	14.0
+70°F	Long.	132,300 (1)	147,800	27.5	53.1	14.8
+70°F	Trans.	133,200 (1)	156,400	26.5	34.8	10.0
+70°F	Trans.	133,000 (1)	154,000	25.5	38.0	10.2
-320°F	Long.	225,300 (1)	232,800	11.1	30.0	9.5
-320°F	Long.	229,200 (1)	234,200	13.3	38.8	9.8
-320°F	Trans.	236,800 (1)	244,300	13.3	23.6	8.0
-320°F	Trans.	236,100 (1)	245,100	11.1	22.0	8.4
+70°F	Long.	137,000 (2)	156,100	16.2	52.6	17.7
+70°F	Long.	138,100 (2)	153,300	16.2	45.1	15.0
-320°F	Long.	228,700 (2)	236,400	11.1	36.4	10.0
-320°F	Long.	237,800 (2)	244,100	11.8	27.5	9.0
+70°F	Trans, base metal	140,800 (3)	153,500	10	27.9	-
-320°F	Trans, base metal	220,700 (3)	228,600	8	26.2	-
+70°F	Trans,	140,100 (4)	153,100	8	22.0	-
-320°F	Thru pressure weld	232,800 (4)	238,800	8	31.9	-

NOTES:

(1) Specimens from same forging, Fed. Std. 151, Specimen R4, 0.160" diam.

(2) Specimens from another forging, Fed. Std. 151, Specimen R4, 0.160" diam.

(3) Specimens from base metal of another forging, 0.113" diam., 0.625" gage length.

(4) Specimens with pressure weld transverse to middle of gage length. 0.113" diam., 0.625" gage length. Specimens machined after pressure welding and heat treating.

(5) Double width, half thickness of standard 0.394" square specimens, with half standard depth.

All forgings were heat treated. 1725° - 1750°F for 2-4 hours, water quenched, aged 1025° - 1050°F for 4-8 hours, air cooled.

TABLE XVIII

Mechanical Properties of Titanium 6Al-4V Alloy

0.75" Thick Forging - TMCA, Heat No. and Chemistry Unknown

FORGING AND HEAT TREATMENT	TEST TEMP.	YIELD STRENGTH psi	TENSILE (1) STRENGTH psi	% ELONG.	% R.A.	NOTCHED (2) TENSILE STRENGTH psi	NOTCHED/ UNNOTCHED TENSILE RATIO
Low finish forging temperature, air cooled,	+78°F	176,800	187,800	10.9	37.3	-	-
heated to 1725°F, 1 hr., water quenched, 1050°F, 3 hrs., air cooled.	-320°F	238,000	253,400	8.7	33.9	254,000	1.00
Forged at 1850°F, cooled, heated to 1725°F, 1 hr., water quenched, 1050°F, 3 hrs.	+78°F	143,300	172,500	10.0	15.0	-	-
air cooled.	-320°F	239,700	253,600	3.8	7.4	236,500	0.93

(1) Standard 0.252" diameter tensile test specimen, 1.0" gage length.

(2) Notched tensile specimen, 0.283" diameter away from notch, circumferentially notched to diameter under notch of 0.200", 60° angle notch, root radius .0025", Stress Concentration, K_t=6.3.

TABLE XIX

Mechanical Properties of Welded Joints in Titanium 6Al-4V Alloy

Plate, Heli-arc Butt Welds, "V" Joints, Welds Completed with 4 Passes of Filler Wire.

TEST	STRESS RELIEVED			HEAT TREATED		
	6Al-4V Filler Wire	3.5Al-2.5V Filler Wire	Ti75A Filler Wire	6Al-4V Filler Wire	3.5Al-2.5V Filler Wire	T175A Filler Wire
Tensile Strength, +70°F, weld machined	139,400 139,500	127,600 128,400	101,800 98,280	171,200 168,300	147,200 139,400	115,700 119,800
Tensile Strength, +70°F, weld not machined	141,700 140,700	136,800 137,500	129,200 125,800	173,900 173,500	170,600 166,000	132,700 139,900
Tensile Strength -320°F, weld machined flush	217,600	198,400 203,800	168,700 173,300	248,000 246,300	209,500 180,600	134,200 117,100
Tensile Strength, -320°F, weld not machined	220,200 221,800	219,300 219,400	185,000 195,700	249,500 251,000	232,500 228,600	157,800 157,200
% Elong., +70°F, weld machined flush	11.0 11.0	4.0 3.0	3.0 3.0	4.0 4.5	3.5 2.5	2.0 1.5
% Elong., +70°F, weld not machined	13.5 12.5	14.5 8.5	5.0 4.5	12.0 12.0	5.0 4.0	3.0 4.0
% Elong., -320°F, weld mahcined flush	11.5	3.5 2.5	3.0 2.5	2.0 2.0	1.5 2.0	1.0 1.0
% Elong., -320°F weld not machined	17.0	28.5	4.0 4.5	3.0 7.0	4.5 3.5	2.0 3.0
V-Notch Charpy, +70°F, ft. lbs.	17.0 10.0	21.5 22.0	25.9 27.4	10.0 8.0	23.0 20.8	6.0 7.0
V-Notch Charpy, -320°F, ft. lbs.	7.4 6.2	10.5 10.8	16.7 13.5	4.0 5.1	10.5 13.5	5.0 4.0

NOTES:

Stress relieved - 1300°F - 1 hr. at temp. air cooled, after welding.

Heat treated - 1725°F - 1 hr. at temp., water quenched, aged at 1050°F - 2 hrs., air cooled, after welding.

Tensile test specimens - Fed. Std. 151, Type F2, flat test specimen, weld transverse to axis.

V-Notch Charpy test specimens - Twice standard width, half standard thickness, 1/2 standard depth of notch; notched in weld metal.

TABLE XX

Mechanical Properties of Titanium 13V-11Cr-3Al Alloy

0.062" Sheet, Crucible, Solution Annealed (1400°F, 30 Min., AC)

TEST TEMP.	DIRECTION		F_{ty} ksi	F_{tu} ksi	el. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.		-	135	22	161	
	Long.		-	135	22	162	
	Long.					160	
		Ave.	-	135	22	161	1.19
-320°F	Long.		-	288	-	149	
	Long.					180	
	Long.					87	
	Long.					220	
		Ave.		288	-	159	0.55
-423°F	Long.					133	
						131	
		Ave.				132	

TABLE XXI

Mechanical Properties of Titanium 13V-11Cr-3Al Alloy

0.062" Sheet, Crucible, S.T. And Aged (900°F, 20 Hr., A.C.)

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	el. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78	Long.	159	176	8	173	
	Long.	-	-	-	173	
	Ave.	159	176	8	173	0.98
-320°F	Long.				129	
	Long.				145	
	Ave.	—	—	—	137	
-423°F	Long.				99.7	
	Long.				83.1	
	Ave.	—	—	—	91.4	

0.062" Sheet, Crucible, S.T. And Aged (900°F, 72 Hr., A.C.)

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	el. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.	181	201	6	169	
	Long.				160	
	Ave.	181	201	6	165	0.82
-320°F	Long.				127	
	Long.				93	
	Ave.	—	—	—	110	
-423°F	Long.				97	
	Long.				119	
	Ave.	—	—	—	109	

TABLE XXII

Mechanical Properties of Titanium 13V-11Cr-3Al Alloy

0.250 Plate, Crucible, Heat R-98103

As Received - Mill Annealed

DIRECTION	TEST TEMP., °F	YIELD STRENGTH 0.2% OFFSET, psi	TENSILE (1) STRENGTH psi	% ELONG.	% R.S.	(2) V-NOTCH CHARPY IMPACT ft. lbs.
Trans.	+70	140,600	150,400	18.8	54.0	6.0
Trans.	+70	140,400	148,200	17.2	53.0	-
Long.	+70	136,300	144,300	21.9	55.0	-
Long.	+70	137,700	145,800	18.8	54.0	-
Trans.	-320	-	251,700	1.5	1.5	1.4
Trans.	-320	-	239,800	1.5	0	1.5
Long.	-320	-	148,400	1.5	0.5	-
Long.	-320	-	197,000	1.5	1.0	-

Annealed at Convair-Astronautics, Heated to 1400°F, held 30 minutes, air cooled

DIRECTION	TEST TEMP., °F	YIELD STRENGTH 0.2% OFFSET, psi	TENSILE (1) STRENGTH psi	% ELONG.	% R.S.	(2) V-NOTCH CHARPY IMPACT ft. lbs.
Trans.	+70	139,200	144,100	21.9	54.0	10.0
Trans.	+70	137,600	144,900	17.2	52.0	9.9
Long.	+70	133,500	140,900	23.4	59.0	-
Long.	+70	134,200	141,500	21.9	56.0	-
Trans.	-320	-	214,900	1.5	0.5	1.3
Trans.	-320	-	246,300	4.6	1.5	1.5
Long.	-320	-	234,800	1.5	1.0	-
Long.	-320	-	265,800	1.5	0	-

NOTES:

(1) Tensile test specimens were 0.160" diameter round shank, with 0.64" gage length.

(2) V-Notch Charpy specimens were twice standard width (0.788"), 1/2 standard thickness (0.197"), and 1/2 standard notch depth (0.039"), but with standard notch contour.

REFERENCES

1. Holden, F. C., Schwartzberg, F. R., and Ogden, H. R., "Tensile Properties of Titanium Alloys at Low Temperatures", DMIC Report 107, January 15, 1959.

2. McClintock, R. M., and Gibbons, H. P., "A Compilation of Mechanical Properties of Materials at Cryogenic Temperatures," NBS Rep. 6064, July 1, 1959.

3. McGee, R. L., Campbell, J. E., Carlson, R. L., and Manning, G. K., "How Low Temperatures Affect Nine High-Strength Alloys," Materials in Design Eng., November 1959, pp. 106-107.

4. Espey, G. B., Jones, M. H., and Brown, W. F. Jr., "Sharp-Edge-Notch Tensile Characteristics of Several High Strength Titanium Sheet Alloys at Room and Cryogenic Temperatures," presented at ASTM, Atlantic City, New Jersey, June, 1960.

5. Special ASTM Committee, "Fracture Testing of High-Strength Sheet Materials," Chapter 1, ASTM Bulletin, February, 1960.

6. Low, J. R., "The Relation of Microstructure to Brittle Fracture," Relation of Properties to Microstructure, American Society for Metals, Cleveland, Ohio, 1954, p. 163.

7. Parker, E. R., "Modern Concepts of Flow and Fracture," Trans. ASM, 50, 1958, p. 52.

8. Hurlich, A., Tanalski, T. T., Watson, J. F., and Christian, J. L., Unpublished data, Convair-Astronautics.

9. Watson, J. F., and Christian, J. L., "Cryostat and Accessories for Tensile Testing at -423°F," to be published in Bulletin, ASTM.

2 December 1960

SUBJECT: Mechanical Properties of Aluminum Alloys at Cryogenic Temperatures

ABSTRACT: This report contains the mechanical property data obtained in the Materials Research Group on aluminum alloys at +78°F, -100°F, -320°F and -423°F. The data include tensile strengths, 0.2% offset yield strengths, elongations, notched tensile strengths, notched/unnotched tensile ratios on parent metal and tensile strengths, elongations and joint efficiencies of welded joints (heliarc butt welds and fusion welds with filler metal added). Materials tested include 2014-T6, 2024-T3, 2024-T4, 2219-T81, 2219-T87, 5052-H38, 5086-H34, 5086-H38, 5154-H38, 5456-H343, 6061-T4, 6061-T6, 7075-T6, 7079-T6, 7178-T6 and X7275-T6 sheet, 2024-T4, 6061-T6 and 7075-T6 plate and 7079-T6 billet material.

An analysis of the results is included for each alloy which primarily discusses the usefulness of the material for structural applications at cryogenic temperatures. Also, correlations of the material's mechanical properties are made with its chemistry, impurity content, microstructure, primary working and heat treatment. Recommendations are made concerning the use of aluminum alloys at cryogenic temperatures and future research work which has been suggested by this program.

Prepared by J. L. Christian
J. L. Christian

Approved by A. Hurlich
A. Hurlich
Research Group Engineer
Materials Research Group

AH:JLC:jfd

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SUBJECT: Mechanical Properties of Aluminum Alloys at Cryogenic Temperatures

INTRODUCTION:

Very low temperatures are encountered in current and proposed missiles and space vehicles due to the use of cryogenic propellants such as liquid oxygen and liquid hydrogen (boiling points of -297°F and -423°F, respectively) and due to the near absolute zero temperatures encountered under certain conditions in outer space. Therefore, the properties of engineering materials at these extreme subzero temperatures are becoming of prime importance to the design engineer.

The primary purpose of this investigation was to determine the mechanical properties of a number of high-strength aluminum alloys in order to evaluate their usefulness for structural applications at cryogenic temperatures. Also, it was the pruposc of this program to correlate the mechanical properties with such variables as chemistry, impurity content, microstructure, primary working, and heat treatment in order to better understand the mode of deformation and fracture characteristics of aluminum alloys as a function of temperature. Another purpose was to make definite recommendations for the future development of aluminum alloys in order to improve their properties at cryogenic temperatures. The materials tested in this program include 2014, 2024, 2219, 5052, 5083, 5086, 5154, 5456, 6061, 7075, 7079, 7178 and X7275 aluminum alloys in various tempers and degree of cold work and in several forms (sheet, plate and forging stock).

Many investigations have been made on the low temperature properties of aluminum alloys (Refs. 1, 2, 3, 4); however, in addition to the determination of tensile and elastic properties as a function of temperature, notched tensile properties and notched/unnotched tensile ratios were determined. The notched/unnotched ratios were determined as a function of temperature in order to evaluate the toughness, which is often referred to in terms of resistance to brittle fracture, or notch sensitivity (Refs. 5, 6, 7). A notched specimen with a stress concentration factor (K_t) of 6.3 was selected for use in this investigation because previous axial fatigue tests of complex welded joints and fatigue and burst tests of pressure vessels made of 301 extra full hard stainless steel exhibited excellent correlation with notched/unnotched tensile ratios obtained with this value of K_t over a range of temperatures from 78° to -423°F (Ref. 8). Data were obtained on specimens with less acute notches (e.g., K_t of 2.5-3.0) and were found to be less discriminatory between tough and brittle materials; in fact notched/unnotched ratios of near unity were obtained on some materials which were known to be

brittle (Ref. 8). At the other extreme, however, stress concentration factors of 15 to 18 have been employed by some investigators (Ref. 4) and these tests in general tend to make all materials appear brittle. Thus, notched/unnotched tensile ratios using a K_t of 6.3 have proven to be both discriminatory between tough and brittle materials and to correlate with service behavior.

MATERIALS, TEST SPECIMENS AND APPARATUS:

The aluminum alloys used in this investigation and their history and chemical analyses are listed in Table 1. The tensile specimens used in this investigation are shown in Figure 1. All tensile specimens were inspected and individually measured for area determination. Notched specimens were inspected and measured by means of an optical comparator, and all specimens out of tolerance were rejected. The stress concentration factor (K_t) as determined by $\sqrt{\dfrac{\text{1/2 width between notches}}{\text{radius of the notch}}}$, was 6.3 with "in tolerance" limits of 5.7 to 7.1.

The testing apparatus consisted of a 50,000-lb. Baldwin universal testing machine equipped with a continuous stress-strain recorder and strain pacer. Standard extensometers were used at room temperature and a specially designed cryo-extensometer was used at low temperatures. Specially constructed cryostats were used for testing at sub-zero temperatures; a small open cryostat for -100° and -320°F, and a gas-tight cryostat insulated by a vacuum chamber, liquid nitrogen jacket and foamed polyurethane, for tensile testing at -423°F. A full description of the cryostat, cryo-extensometer, and accessory equipment, as well as the safety features and rapidity of testing can be found in Ref. 9. The tensile machine, extensometers and accessory equipment were periodically checked and calibrated.

EXPERIMENTAL PROCEDURE:

Tensile tests were performed at 78°F (room temperature), -100°F by immersion in a bath of dry ice and alcohol, -320°F by immersion in liquid nitrogen and -423°F by immersion in liquid hydrogen. Tests were conducted after the specimens came to temperature as determined by a copper-constantan thermocouple taped to the test section. Times required to reach temperature were from 2 to 5 minutes after immersion. The smooth tensile specimens were tested at a strain rate of 0.001 in./in./minute to yield, followed by a rate of 0.15 in./minute until fracture. Notched tensile specimens were tested at 0.001 in./in./minute, as determined by extensometers, until fracture. Yield strengths were determined from the continuous stress-strain curves by the 0.2% offset method. Elongations reported herein are total elongations as determined by scribe marks on a surface dye and read at 10X magnification over a 2-in. gage length for flat tensile specimens and a 1-in. gage length for the round test bars. Hardness measurements were made on a Rockwell superficial tester on the 15-N scale at room temperature.

EXPERIMENTAL RESULTS:

The tensile and yield strengths, elongations, notched tensile strengths, notched/unnotched tensile ratios and welded joint properties are presented in Tables II through XXII (see list of tables, page 11).

DISCUSSION OF RESULTS:

Each of the aluminum alloys will be discussed separately, particularly concerning its use for structural applications at cryogenic temperatures; however the behavior of pure aluminum at extreme sub-zero temperatures will be discussed first. Also, a few generalizations on the behavior of aluminum alloys at cryogenic temperatures will be made based upon the present test data.

The following may be said about the effects of low temperatures on the mechanical properties of metals, such as pure aluminum, which have face-centered, cubic lattice structures. (Refs. 10, 11) There is a small increase which is gradual and continuous in the initial resistance to deformation (yield strength) and in the elastic modulus as the temperature is lowered. There is little or no change in ductility as measured by elongation, from room to cryogenic temperatures. Also, there is no detrimental effect on toughness, as determined by impact tests, consequently, there is no ductile to brittle transition (such as is noted in many materials having body-centered cubic or hexogonal-close-packed structures). There is, however, a large increase (50 to 100%) in the tensile strength with reduction in temperature from +78°F to -423°F which is indicative that the hardness and possibly the rate of work hardening is strongly affected by temperature.

As may be seen from the data presented in Tables II through XXII, the aluminum alloys tested in this investigation do not behave in the same manner as pure aluminum at cryogenic temperatures. Yield strengths increase from 25 to 50% by reducing the temperature from +78°F to -423°F. Many of the alloys (7000 series) experienced a sharp decrease in ductility (as measured by elongation and reduction in area) at the lower temperatures. Notched tensile data and notched/unnotched tensile ratios indicate that many of the aluminum alloys (particularly some of the 5000 and 7000 series alloys) became embrittled at cryogenic temperatures. Tensile strengths increased from 25 to 50% instead of 50 to 100% as would be expected for pure aluminum.

Therefore it is seen that low temperatures affect the mechanical properties (yield and tensile strengths, ductility and toughness) of aluminum alloys quite differently as compared to undistorted crystals with face-centered cubic lattice structures. Explanations for the cryogenic behavior of these alloys is based upon the presence of a strained lattice structure, precipitates in the grain boundaries and slip planes, and intermetallic compounds. How large an effect these factors have on the behavior of aluminum alloys depends upon the type and amount of alloying elements and impurities present

and whether they are in solid solution with the parent aluminum or in the form of a second phase.

The large increases in yield strength are felt to be due to the soild solution elements and precipitates within the crystal structure which create a strained or distorted lattice. Many of these strains within the lattice are "locked" in place at the lower testing temperatures thereby causing a large increase in the initial resistance to deformation (yield strength). The sharp decline in ductility of some of the 7000 series alloys is explained on the basis of "premature" fractures caused by stress concentrations (inclusions or large precipitates) within the grain and, or heavy precipitation at the grain boundaries which creates a brittle condition. Photomicrographs of fractured tensile specimens show these conditions (Ref. 12). The rate of work hardening for the aluminum alloys apparently was not strongly affected by decrease in temperature. This is shown by the fact that there was a smaller increase in tensile strength than is experienced in pure aluminum, that the hardness (15-N scale) of the fractured specimens near the fractures was nearly the same as for the untested material, and that slip lines appeared in only a few grains (Ref. 12). The decrease in toughness, as measured by the trend of the notched tensile strength and notched/unnotched tensile ratios, at the lower testing temperatures is felt to be due to the presence of a strained lattice and stress concentrators (precipitates and inclusions).

As may be seen from the data in Tables II through XXII, the 2000 and 6000 series alloys behave more like pure aluminum at cryogenic temperatures than do the 7000 series and the high Mg containing 5000 series alloys (5154 and 5456). This is explained on the basis that the total alloying content is much higher in the 7000 series and high Mg 5000 series alloys.

There appears to be a definite effect on the low temperature toughness as a result of various heat treatments. For example, the 6061-T6 alloy retains greater toughness than the 6061-T4 at -423°F; also the 2024-T4 remains tougher than 2024-T3. These data are explained on the basis that more of the alloying elements are precipitated out in the form of discrete particles of intermetallic compounds in the 6061-T6 and 2024-T4 than in the 6061-T4 and 2024-T3 which gives a less distorted lattice and therefore greater toughness for the 6061-T6 and 2024-T4 materials.

As witnessed by the data on 5086-H34 (half hard) and 5086-H38 (full hard), there is little effect as a result of the amount of working (cold rolling) in these alloys since both of these alloys retain about the same degree of toughness at cryogenic temperatures.

The notched/unnotched tensile ratios for the plate and billet materials were appreciably higher than for the corresponding sheet materials at room temperature. These data may be explained by the distortion energy theory

(Ref. 11), which also explains why notched/unnotched tensile ratios greater than unity may be obtained. The distortion energy theory states that the total stress-strain curve (elastic and plastic regions) is raised under conditions of biaxial loading and even more so for triaxial loading than for simple tension. Therefore, due to the biaxial loading present in notched sheet specimens and triaxial loading in notched bar specimens, it is possible to obtain notched/unnotched values of 1.1 and 1.3, respectively. For this reason a comparison of data obtained from flat specimens (sheet material) and round specimens (plate material) is not attempted.

2000 SERIES ALUMINUM ALLOYS:

Based on the notched tensile strengths and notched/unnotched tensile ratios, it is felt that the following 2000 series aluminum alloys may be used for structural applications at -423°F: 2014-T6, 2024-T4, 2219-T81 and 2219-T87 sheet and 2024-T4 plate. 2024-T3 sheet may be used to -320°F. Table XXIII is a Material Selection Guide which indicates at which temperatures the aluminum alloys tested in this investigation may be used for structural applications.

Of the 2000 series alloys, 2014-T6 has the highest strength (60 + ksi F_{ty} and 70 + ksi F_{tu} at 78°F) with an appreciable increase in tensile properties at cryogenic temperatures (80 + ksi F_{ty} and 100 + ksi F_{tu} at -423°F). Elongation of the base metal remains uniform at all testing temperatures. Welded joints (manually welded by the tungsten arc method with 2319 filler metal, tested with bead in place) are 70 + % efficient at all testing temperatures. Elongations of welded joint specimens were low (2% at 78°F and 1.2% at -423°F); however there was no indication of embrittlement in the weld or heat affected zone as determined by notched tensile tests. Further information (e.g. cost, availability, formability, etc.) on 2014-T6 is available in MRG-192-2.

2219-T81 and -T87 are the next higher strength 2000 series alloys. 2219 was recently developed as a high temperature alloy; however it shows great promise for cryogenic applications. Weld joint efficiencies and elongations are simular for 2219 as they were for the 2014-T6 alloy. 2024-T4 in both sheet and plate remains tough to -423°F; however this alloy is of lower strength. The toughness of 2024-T3 is questionable at -423°F. 2024-T3 is not recommended for structural applications which must withstand high stresses or impact loading at -423°F.

At the present time there is a paucity of fatigue data on aluminum alloys at cryogenic temperatures, particulary on welded joints and at high stress levels. It is felt that fatigue data should be obtained on those alloys which appear to be the most promising for cryogenic applications.

5000 SERIES ALUMINUM ALLOYS

Of the 5000 series aluminum alloys, 5052-H38 and 5083-H38 appear to remain

tough enough for structural applications at -423°F. 5086-H34 and -H38 and 5154-H38 may be used to -320°F. Notched tensile data indicate that 5456-H343 suffers some degree of embrittlement even at -100°F; therefore this alloy is not recommended for cryogenic applications.

Of the two 5000 series alloys acceptable for use at -423°F the 5083-H38 has the highest strength (see Table IX); however this material was experimentally rolled to the H38 temper. It is felt that this material should be more thoroughly evaluated before being used at -423°F. Data obtained on welded joints (heliarc butt weld, roll planished, no filler metal) are presented in Tables VIII, X, XII and XIII for 5052-H38, 5086-H34, 5154-H38 and 5456-H343. Welded joint efficiencies ranged from about 65 to 85% depending upon the material and testing temperature. Base metal and weld elongations generally increased with reduction in temperature. As was mentioned previously, the poor toughness of some of the 5000 series alloys (e.g. 5456) is felt to be due to the highly strained lattice resulting from the large amount of alloying content in solid solution or precipitated in the crystal structure. At the present time more information is available on the 5052 alloy (see MRG-192-2); therefore it is recommended for use at -423°F in preference to 5083 until further data may be obtained.

6000 SERIES ALUMINUM ALLOYS

6061-T6 sheet and plate remain sufficiently tough for structural applications to -423°F. 6061-T4 appears to become embrittled at the lower testing temperatures and is not recommended for use at -423°F. The strength of 6061 is significantly less than other aluminum alloys (e.g. 2014) which remain tough to -423°F. Weld data were not obtained.

7000 SERIES ALUMINUM ALLOYS

The notched tensile strengths which indicate notch sensitivity and the notched/unnotched tensile ratios which may be used as indices for resistance to brittle fracture show that all the 7000 series aluminum alloys suffer a degree of embrittlement at very low temperatures. As may be seen in Tables XVII through XXII, notched/unnotched tensile ratios are considerably less than unity for 7178 at -100°F, for 7075, 7275 and 7178 at -320°F and for all of the 7000 series aluminum alloys at -423°F.

The poor toughness, as measured by the notched/unnotched tensile ratio, of these alloys at cryogenic temperature is felt to be primarily due to the chemistry (high alloying content) and to the impurities present. The toughness of the 6000, 5000 and 2000 series aluminum alloys, representing low alloying, magnesium alloying, and copper alloying, respectively, is not as severely impaired at low temperatures (Refs. 1, 3, 4, 8) as for the 7000 series alloys. Therefore, it appears that the high alloying (Zn, Mg, Cu) contents, and in particular, the zinc additions are primarily responsible for the low temperature embrittlement. Further evidence of this effect may be seen by comparing the chemistry of 7079 sheet material which has nearly

the same total alloying content but much smaller amounts of zinc and copper, with the rest of the 7000 series alloys. This alloy retains greater toughness at much lower temperatures than the 7075, 7275 or 7178 alloys. That impurity content is a factor controlling low temperature embrittlement is apparent from the fact that 7275-T6 retains greater toughness to -320°F than 7075-T6. As may be seen in Table 1, 7275 is merely a high purity 7075 alloy and as such has far fewer inclusions present in the microstructure. Also, the abnormally low transverse properties of 7075-T6 plate may be explained due to the large number of inclusions present in the grain boundaries.

The second important factor effecting low temperature embrittlement of the 7000 series aluminum alloys is that of primary working. The degree of primary working of the metal is important as may be seen by comparing the properties of the 7079-T6 sheet and 7079-T6 billet material. Chemistries were nearly identical; however, the billet material experienced much more severe embrittlement at lower temperatures than the sheet material. This may be explained by the cored structure present in the 7079-T6 billet, which was not broken up by primary working.

Based upon the data obtained in this investigation, it is recommended that extreme caution be exercised in employing any of the 7000 series alloys for low temperature structural applications in which high stresses and impact loading are present. In fact; it is recommended that none of these alloys be used for such applications below -320°F, that only 7079-T6 sheet material be employed at less than -100°F, and that 7178-T6 sheet material not be used much below room temperature. These recommendations are based upon present information; however it is felt that future development may considerably improve the low temperature properties of these alloys. In view of the above mentioned factors which effect low temperature embrittlement, it is suggested that further development of the 7000 series alloys for the purpose of improving their cryogenic properties be concerned with chemistry, impurity content, and degree of primary working. Research along these lines is presently being initiated in the Materials Research Group.

RECOMMENDATIONS:

Based upon the data obtained in this investigation, the following aluminum alloys may be used for structural applications at -423°F: 2014-T6, 2024-T4, 2219-T81, 2219-T87, 5052-H38, 5083-H38 and 6061-T6 sheet and 2024-T4 and 6061-T6 plate. These alloys as well as the following alloys may be used for structural applications down to -320°F: 2024-T3, 5086-H34, 5086-H38, 5154-H38, 6061-T4 and 7079-T6 sheet. Two of the aluminum alloys tested are not recommended for use at any sub-zero temperature (5456-H343 and 7178-T6). Table XIII is a Material Selection Guide which is added for convenience in selecting those alloys which may be used at extreme sub-zero temperatures. These recommendations are based upon present data which was generally obtained on only one lot (heat) aluminum for each alloy; therefore further testing

(tensile, notched tensile and fatigue) should be conducted before using the above mentioned alloys in a major structure at cryogenic temperatures.

In addition to further evaluation of the more promising alloys, it is felt that more research should be conducted to further determine the effects of chemistry, impurities, microstructure, primary working and heat treatment on the properties of aluminum alloys at cryogenic temperatures. The purpose of this research is to develop aluminum alloys of higher strength commensurate with adequate toughness for use at cryogenic temperatures.

CONCLUSIONS:

1. Based upon notched tensile strengths and notched/unnotched tensile ratios, the following aluminum alloys may be used for structural applications at -423°F: 2014-T6, 2024-T4, 2219-T81, 2219-T87, 5052-H38, 5083-H38 and 6061-T6 sheet and 2024-T4 and 6061-T6 plate.

2. In addition to the above mentioned alloys, 2024-T3, 5086-H34, 5086-H38, 5154-H38, 6061-T4 and 7079-T6 sheet may be used to -320°F.

3. 7075-T6 sheet and plate and X7275-T6 sheet may be used to -100°F; 5456-H343 and 7178-T6 sheet should not be used at any sub-zero temperature (-100°F or below).

4. In general, the mechanical properties of aluminum alloys are affected quite differently as compared to the mechanical properties of pure aluminum at cryogenic temperatures.

5. The large increases in yield strengths of aluminum alloys with reduction in temperature is felt to be due to the strained lattice created by alloying elements, impurities and precipitates within the crystal.

6. The sharp reduction in ductility noted for some of the 7000 series alloys at -320°F and at -423°F is felt to be due to "premature" fractures caused by stress concentrators (inclusions and large precipitates) and brittle grain boundaries (caused by heavy precipitation in the grain boundaries).

7. Aluminum alloys experienced less work hardening at cryogenic temperatures than pure aluminum, as determined by relatively small increases in F_{tu}, little or no increase in hardness and the appearance of only a few slip lines in the microstructures of fractured specimens.

8. The decrease in toughness in some of the aluminum alloys at reduced temperatures is felt to be due to one or more of the following: strained lattice, stress concentrators (inclusions, etc.) and brittle grain boundaries.

9. Notched/unnotched tensile ratios on round (bar) specimens are not the same as for flat (sheet) specimens. The explanation is based on the distortion energy theory.

10. There appears to be a definite effect of various heat treatments on the toughness of several alloys at cryogenic temperatures. This is explained on the basis of the degree of strain within the lattice as a result of the amount of alloying elements in solid solution.

11. There seems to be little or no effect (within the limits tested) of the amount of primary working (cold rolling) upon the toughness of the 5000 series alloys at cryogenic temperatures. However, as seen by the data on 7079-T6 billet material, sufficient working to break up the cored (as cast) structure is required to improve the toughness at cryogenic temperatures.

LIST OF TABLES

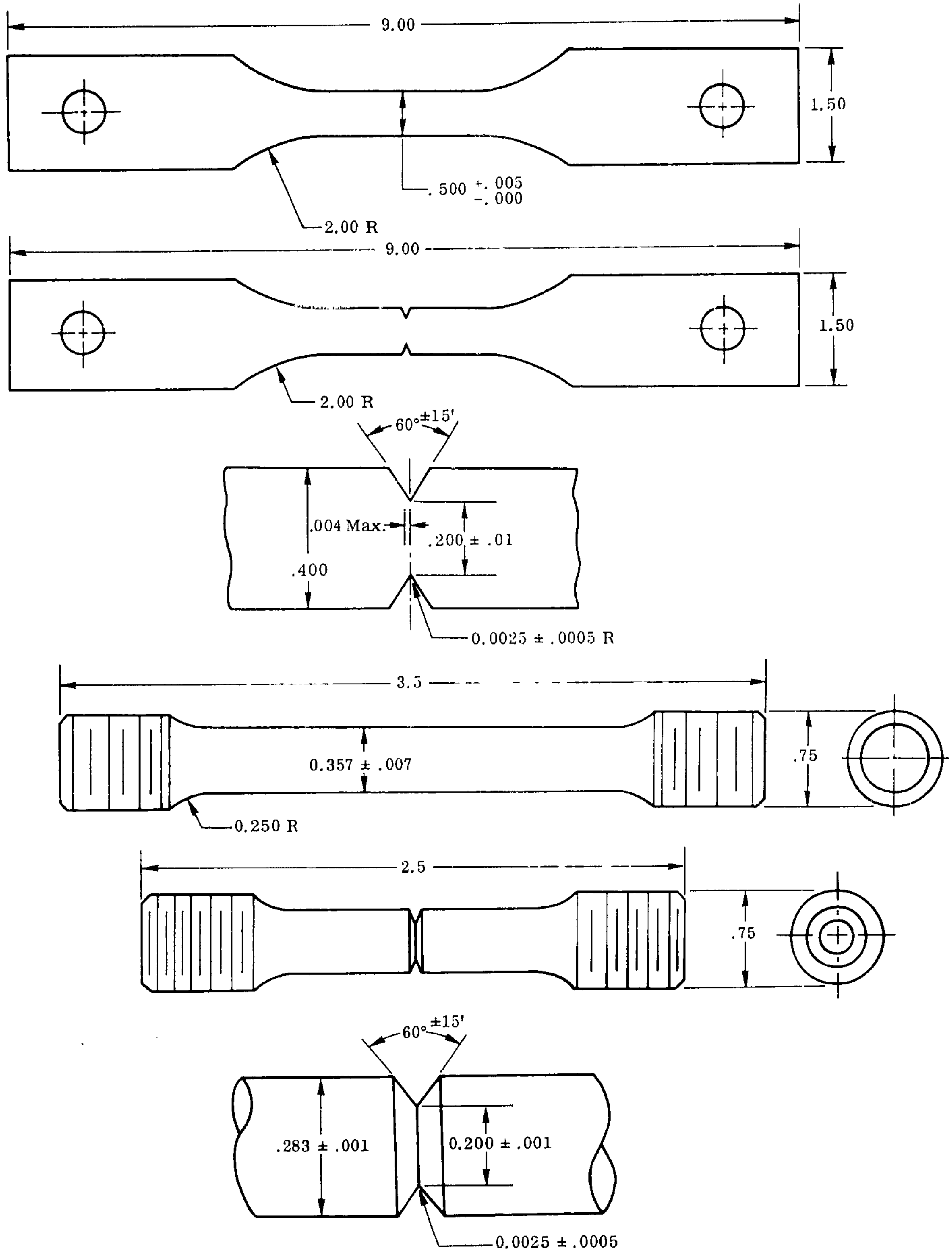

Fig. 1. Tensile specimens for cryogenic testing (all dimensions in inches).

TABLE I

History and Chemical Analysis of Aluminum Alloys

MATERIAL TEMPER - FORM	GAUGE (in.)	SPECIFICATION OR HEAT NO.	SUPPLIER	CHEMISTRY Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn
2014-T6 Sheet	0.063	AMS 4029	Alcoa	-	4.37	0.36	0.23	0.62	0.69	0.018	-
2024-T3 Sheet	0.025	QQ-A-355	Alcoa	0.01	4.80	0.32	1.46	0.55	0.19	0.02	0.21
2024-T4 Sheet	0.032	QQ-A-355	Alcoa	-	4.35	0.31	1.34	0.51	0.15	0.015	-
2024-T4 Plate	2.0	QQ-A-355	Alcoa	0.01	4.83	0.73	1.84	0.92	0.26	0.02	0.25
2219-T81 Sheet	0.063		Alcoa	-	5.8	0.10	0.01	0.29	0.1	0.066	-
2219-T87 Sheet	0.063		Alcoa	-	6.0	0.15	0.01	0.37	0.1	0.068	-
5052-H38 Sheet	0.040	635-521	Alcoa	0.172	0.045	0.249	2.59	-	0.11	0.011	-
5083-H38 Sheet	0.050	Experimental	Kaiser	0.12	0.04	0.14	4.50	0.30	0.11	0.02	0.04
5086-H34 Sheet	0.040	106-404	Alcoa	0.11	0.05	0.18	3.66	0.37	0.11	0.01	-
5086-H38 Sheet	0.050	Experimental	Kaiser	0.15	0.04	0.27	3.93	0.45	0.12	0.02	0.06
5154-H38 Sheet	0.040	667-471	Alcoa	0.21	0.03	0.22	3.38	-	0.12	0.10	-
5456-H343 Sheet	0.050	Mil-A19842	Alcoa	0.08	0.06	0.22	5.27	0.81	0.13	0.02	0.03
6061-T4 Sheet	0.025	QQ-A-327	Kaiser	0.19	0.15	0.50	0.95	0.09	0.56	0.03	0.17
6061-T6 Sheet	0.020	QQ-A-327	Kaiser	0.18	0.23	0.37	0.94	0.08	0.76	0.06	0.05
6061-T6 Plate	1.0	QQ-A-327	Kaiser	0.37	0.28	0.66	1.23	0.08	0.83	0.02	0.10
7075-T6 Sheet	0.025	QQ-A-283	Alcoa	0.23	1.47	0.32	2.45	0.04	0.15	0.05	5.85
7075-T6 Plate	2.5	QQ-A-283	Kaiser	0.185	1.43	0.25	2.75	0.044	0.14	0.039	5.46
7079-T6 Sheet	0.080		Kaiser	0.16	0.64	0.12	3.46	0.20	0.14	0.03	4.34
7079-T6 Billet	5.0	0-01041	Alcoa	0.13	0.71	-	3.30	0.14	0.1	0.06	4.15
7178-T6 Sheet	0.036	Mil-A-9180A	Kaiser	0.26	1.95	0.21	3.0	0.04	0.11	0.02	6.6
X7275-T6 Sheet	0.050	Experimental	Kaiser	0.17	1.58	0.04	2.70	0.04	0.05	0.04	5.74

TABLE II

Mechanical Properties of 2014-T6 Aluminum Alloy

0.063" Sheet, Alcoa, AMS 4029

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	e %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/ UNNOTCHED TENSILE RATIO	WELD TENSILE* STRENGTH (ksi)	WELD ELONG %	JOINT EFF %
+78	Long.	66.3	73.7	11	74.8		51.2	2.0	
	Long.	65.1	72.5	11	74.1		54.8	2.0	
	Long.						53.4	1.5	
	Avg	65.7	73.1	11	74.5	1.02	53.1	2.0	73
+78	Trans.	62.5	71.4	11	70.9				
	Trans.	63.0	71.9	11	71.6				
	Trans.	63.0	71.3	11	67.5				
	Avg	62.8	71.5	11	70.0	0.98			
-100	Long.	69.2	76.5	12	79.6		55.8	1.5	
	Long.	69.3	76.3	12	78.7		58.8	2.5	
	Long.						55.5	1.5	
	Avg	69.3	76.4	12	79.2	1.04	56.7	2.0	74
-100	Trans.	64.5	74.6	12	71.5				
	Trans.	64.8	74.1	11	70.3				
	Trans.	63.6	73.5	11	71.2				
	Avg	64.3	74.1	11	71.0	0.96			
-320	Long.	74.4	87.4	14	85.3		60.9	1.0	
	Long	-	86.8	14	85.6		63.2	1.0	
	Long.						61.6	1.0	
	Avg	74.4	87.1	14	85.5	0.98	61.9	1.0	71
-320	Trans.	71.8	85.1	14	79.8				
	Trans.	66.6	79.7	14	75.9				
	Trans.	72.6	86.1	13	80.3				
	Avg	70.3	78.7	14	78.7	1.00			
-423	Long.	87.4	105	18	100		71.7	1.0	
	Long.	85.0	103	16	95.5		83.6	1.0	
	Long.						71.4	1.5	
	Avg	86.2	104	17	97.8	0.94	75.6	1.2	73
-423	Trans.	80.2	101	15	85.4				
	Trans.	83.5	104	15	86.3				
	Trans.	83.2	101	15	81.8				
	Avg	82.3	102	15	84.5	0.83			

*Filler Metal (2319) weld, tested with bead in place.

TABLE III

Mechanical Properties of 2024-T3 Aluminum Alloy

0.025" Sheet, Alcoa, QQ-A-355

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	el. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.	47.8	67.8	18	59.9	
	Long.	47.5	68.1	18	59.8	
	Long.	47.0	67.9	18	60.8	
	Ave.	47.4	67.9	18	60.2	0.89
+78°F	Trans.	43.8	66.2	18	62.6	
	Trans.	43.9	65.4	18	63.1	
	Ave.	43.9	65.8	18	62.9	0.96
-100°F	Long.	49.4	70.3	21	60.0	
	Long.	49.2	70.5	21	61.2	
	Long.	48.1	69.9	20	62.3	
	Ave.	48.9	70.2	21	61.2	0.87
-100°F	Trans.	44.0	67.9	21	62.7	
	Trans.	45.0	67.7	21	62.8	
	Ave.	44.5	67.8	21	62.8	0.93
-320°F	Long.	61.0	86.1	22	76.6	
	Long.	61.4	87.8	22	76.6	
	Long.	60.2	87.2	22	75.4	
	Ave.	60.9	87.0	22	76.2	0.88
-320°F	Trans.	56.5	83.2	22	75.4	
	Trans.	55.7	83.5	22	73.9	
	Ave.	56.1	83.4	22	74.7	0.90
-423°F	Long.	-	109	19	88.3	
	Long.	70.9	110	14	84.8	
	Long.	75.2	112	19	95.2	
	Long.				86.7	
	Ave.	73.1	110	17	88.8	0.81
-423°F	Trans.	68.9	106	19	85.4	
	Trans.	69.0	107	17	88.2	
	Ave.	69.0	107	18	86.8	0.81

TABLE IV

Mechanical Properties of 2024-T4 Aluminum Alloy

0.032" Sheet, Alcoa, QQ-A-355

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	el. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.	42.6	67.5	19	58.3	
	Long.	42.9	66.9	19	59.2	
	Long.	43.0	68.6	18	59.5	
	Ave.	42.8	67.7	19	59.0	0.87
+78°F	Trans.	40.5	64.8	20	57.5	
	Trans.	42.4	69.4	20	57.5	
	Ave.	41.5	67.1	20	57.5	0.86
-100°F	Long.	43.0	70.1	24	60.1	
	Long.	44.1	69.6	20	60.4	
	Long.	44.1	69.6	21	61.7	
	Ave.	43.7	69.8	22	60.7	0.87
-100°F	Trans.	42.4	67.2	25	58.9	
	Trans.	43.0	68.8	23		
	Ave.	42.7	68.0	24	58.9	0.87
-320°F	Long.	54.8	86.0	32	71.3	
	Long.	55.0	83.9	24	71.2	
	Long.	52.4	84.8	24	73.3	
	Ave.	54.1	84.9	27	71.9	0.85
-320°F	Trans.	53.7	81.3	16	65.7	
	Trans.	53.5	82.2	21	70.6	
	Ave.	53.6	81.8	19	68.2	0.83
-423°F	Long.	74.3	103	12	85.3	
	Long.	74.8	108	19	86.9	
	Long.	70.9	110	17	91.2	
	Long.				89.8	
	Ave.	73.3	107	16	88.3	0.83
-423°F	Trans.	66.8	94.3	10	85.6	
	Trans.	68.2	99.8	10	85.1	
	Ave.	67.5	97.1	10	85.4	0.88

TABLE V

Mechanical Properties of 2024-T4 Aluminum Alloy

2.0" Plate, Alcoa, QQ-A-355

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	e %	R. A. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHE TENSILE RATIO
+78°F	Long	56.7	71.5	19	12	82.4	
	Long.	53.6	67.9	22	22	79.6	
	Long.	53.3	70.0	21	18	84.8	
	Ave.	54.5	69.8	21	17	82.3	1.18
+78°F	Trans.	45.3	66.3	16	15	77.2	
	Trans.	45.7	67.5	16	15	75.3	
	Trans.					76.0	
	Ave.	45.5	66.9	16	15	76.2	1.14
-100°F	Long.	55.3	69.6	19	4	84.1	
	Long.	56.0	69.1	16	2	84.2	
	Long.	55.0	71.9	21	5	82.8	
	Ave.	55.4	70.2	19	4	83.7	1.19
-100°F	Trans.	-	65.3	-	5	80.4	
	Trans.	45.2	67.4	16	12	74.4	
	Ave.	45.2	66.4	16	9	77.4	1.17
-320°F	Long.	65.9	81.5	13	11	95.4	
	Long.	67.4	81.7	6	12	96.6	
	Long.	-	83.7	16	11	100	
	Ave.	66.7	82.3	12	11	97.3	1.18
-320°F	Trans.	50.7	80.7	17	12	90.3	
	Trans.	-	80.4	12	-	89.4	
	Ave.	50.7	80.6	15	12	89.9	1.12
-423°F	Long.	79.9	95.5	8	5	112	
	Long.	80.1	95.8	13	10	111	
	Long.	79.9	95.0	10	12	110	
	Ave.	80.0	95.4	10	9	111	1.16
-423°F	Trans.					95	
	Trans.	69.4	93.6	8	9	95	
	Ave.	69.4	93.6	8	9	95	1.01

TABLE VI

Mechanical Properties of 2219-T81 Aluminum Alloy

0.063" Sheet, Alcoa

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	e %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/ UNNOTCHED TENSILE RATIO	* WELD TENSILE* STRENGTH (ksi)	WELD ELONG (%)	JOINT EFF (%)
+78°F	Long.	52.0	67.4	10	64.1	0.95	47.7	2	
	Long.	51.9	67.6	9	64.7		48.7	3	
	Long.						48.0	3	
	Ave.	52.0	67.5	10	64.4	0.95	48.1	3	71
+78°F	Trans.	51.0	67.2	10	63.0				
	Trans.	51.0	67.2	10	69.0				
	Ave.	51.0	67.2	10	66.0	0.98			
-100°F	Long.	56.5	73.0	9	68.4		50.2	6	
	Long.	56.9	73.5	9	68.8		49.5	4	
	Long.						49.5	4	
	Ave.	56.7	73.3	9	68.6	0.94	49.7	5	68
-100°F	Trans.	54.7	72.2	11	67.1				
	Trans.	54.7	72.3	9	66.8				
	Ave.	54.7	72.3	10	67.0	0.93			
-320°F	Long.	61.7	85.1	11	72.2		63.7	2	
	Long.	62.7	85.3	11	77.5		63.6	2	
	Long.						65.7	4	
	Ave.	62.2	85.2	11	77.4	0.91	64.3	3	75
-320°F	Trans.	61.4	84.6	12	76.7				
	Trans.	-	84.6	12	75.4				
	Ave.	61.4	84.6	12	76.1	0.90			
-423°F	Long.	69.0	100	15	92.3		73.2	2	
	Long.	72.2	103	15	94.5		71.5	2	
	Long.						72.4	2	
	Ave.	70.6	102	15	93.4	0.92	72.4	2	71
-423°F	Trans.	66.8	101	15	94.6				
	Trans.	68.2	102	15	88.0				
	Ave.	67.5	102	15	91.3	0.90			

* Manually welded with 2319 aluminum filler metal, no post heat treatment, tested with bead in place (all fractures occurred in heat effected zone).

TABLE VII

Mechanical Properties of 2219-T87 Aluminum Alloy

0.063" Sheet, Alcoa

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	e %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/* UNNOTCHED TENSILE RATIO	WELD TENSILE STRENGTH (ksi)	WELD ELONG (%)	JOINT EFF (%)
+78°F	Long.	58.3	70.8	9	68.9		50.6	2	
	Long.	58.0	70.6	9	70.5		50.0	2	
	Long.						52.6	3	
	Ave.	58.2	70.7	9	69.7	0.99	51.1	2	72
+78°F	Trans.	58.5	71.1	9	70.6				
	Trans.	58.6	71.1	9	68.8				
	Ave.	58.6	71.1	9	69.7	0.98			
-100°F	Long.	62.4	76.6	9	75.0		50.6	5	
	Long.	62.3	76.1	9	74.2		48.5	3	
	Long.						49.5	3	
	Ave.	62.4	76.4	9	74.6	0.98	49.5	4	65
-100°F	Trans.	61.9	76.4	9	74.8				
	Trans.	63.7	76.3	9	72.5				
	Ave.	62.8	76.4	9	73.7	0.96			
-320°F	Long.	69.4	88.6	11	85.9		61.0	2	
	Long.	70.0	88.2	11	85.0		60.9	2	
	Long.						61.8	2	
	Ave.	69.7	88.4	11	85.5	0.97	61.2	2	69
-320°F	Trans.	70.8	89.3	11	83.6				
	Trans.	70.0	89.4	11	83.8				
	Ave.	70.4	89.4	11	83.7	0.94			
-423°F	Long.	76.6	104	14	95.1		76.4	1.5	
	Long.	76.2	104	14	96.0		70.7	0.5	
	Long.						71.8	0.5	
	Ave.	76.4	104	14	95.6	0.92	73.0	1	70
-423°F	Trans.	76.2	105	14	95.1				
	Trans.	75.6	105	14	95.2				
	Ave.	75.9	105	14	95.2	0.91			

* Manually welded with 2319 aluminum filler metal, no post heat treatment, tested with bead in place (all fractures occurred in heat effected zone).

TABLE VIII

Mechanical Properties of 5052-H38 Aluminum Alloy

.040" Sheet, Alcoa, Heat No. 635-521

TEST TEMP. °F	DIRECTION	F_{ty} ksi	F_{tu} ksi	e %	NOTCHED T.S. ksi (K_t=6.3)	NOTCHED/ UNNOTCHED TENSILE RATIO	HELIARC* BUTT WELD T.S. ksi	WELD ELONG %	JOINT EFF %
+78	Long.	39.7	44.8	7	48.5		30.0	3	
	Long.	40.1	45.2	7	48.1		30.0	3	
	Long.	39.9	45.0	8	48.4		30.0	3	
	Long.	40.5	45.4	7			30.6	4	
	Long.	40.0	45.3	7			30.5	3	
	Avg	40.0	45.1	7	48.3	1.07	30.2	3	67
+78	Tran.	41.1	45.7	9	50.6				
	Tran.	41.9	46.0	9	51.9				
	Tran.				51.2				
	Tran.				50.8				
	Tran.				51.2				
	Avg	41.5	45.9	9	51.1	1.11			
-100	Long.	41.1	47.3	11	50.6		31.4	5	
	Long.	40.7	46.9	11	50.4		32.2	4	
	Long.	41.1	47.1	10			31.7	5	
	Avg.	41.0	47.0	11	50.5	1.07	31.8	4	68
-100	Tran.	41.1	47.2	11	54.2				
	Tran.	42.8	47.9	11	54.1				
	Avg	42.0	47.0	11	54.2	1.13			
-320	Long.	48.7	63.4	24	63.1		45.8	5	
	Long.	48.0	62.4	27	63.2		47.9	5	
	Long.		62.3	18	63.5		46.2	6	
	Long.	47.7	62.8	26			46.9	5	
	Long.	47.6	62.3	30			47.0	5	
	Avg	48.0	62.6	25	63.3	1.01	46.8	5	75
-320	Tran.		59.1	26	64.2				
	Tran.	47.9	58.8	25	63.5				
	Tran.				64.4				
	Tran.				64.0				
	Tran.				64.3				
	Avg	47.9	59.0	26	64.1	1.09			
-423	Long.	54.3	91.2	30	81.0		59.7	7	
	Long.	54.8	88.9	32	81.0		66.5	9	
	Long.	54.9	89.0	32	79.8		57.1	7	
	Long.						72.1	10	
	Long.						69.2	9	
	Avg	54.7	89.7	32	80.6	.90	64.9	9	72
-423	Tran.	56.5	79.7	35	77.7				
	Tran.		82.4	38	78.7				
	Avg	56.5	81.2	37	78.2	.96			

*Heliarc butt weld; x-rayed; roll planished; no doubler reinforcement

TABLE IX

Mechanical Properties of 5083-H38 Aluminum Alloy

0.050" Sheet, Kaiser, Experimental Heat

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	e %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.	57.1	62.5	5	61.8	
	Long.	56.2	62.9	5	62.4	
	Ave.	56.7	62.7	5	62.1	0.99
+78°F	Trans.	55.5	65.0	8	64.5	
	Trans.	56.1	65.2	9	64.0	
	Ave.	55.8	65.1	9	64.3	0.99
-320°F	Long.	65.0	82.4	16	76.7	
	Long.	65.0	81.7	13	77.0	
	Ave.	65.0	82.1	15	76.9	0.94
-320°F	Trans.	65.1	80.8	17	76.7	
	Trans.	64.1	80.3	14	78.2	
	Ave.	64.6	80.6	16	77.5	0.96
-423°F	Long.	71.5	99.2	12	86.7	
	Long.	-	102	13	87.4	
	Ave.	71.5	101	13	87.1	0.86
-423°F	Trans.	72.6	95.2	12	90.5	
	Trans.	79.1	98.7	12	84.1	
	Ave.	75.9	97.0	12	87.3	0.90

TABLE X

Mechanical Properties of 5086-H34 Aluminum Alloy

.040" Sheet, Alcoa, Heat No. 106-404

TEST TEMP. °F	DIRECTION	F_{ty} ksi	F_{tu} ksi	e %	NOTCHED T.S. ksi (K_t=6.3)	NOTCHED/ UNNOTCHED TENSILE RATIO	HELIARC* BUTT WELD T.S. ksi	WELD ELONG %	JOINT EFF %
+78	Long.	35.3	47.6	10	48.7		38.5	3	
	Long.	35.8	48.0	8	48.7		38.3	4	
	Long.		47.3	10	48.6		40.0	4	
	Long.	36.0	48.1	9			39.0	4	
	Long.	35.7	48.1	9			39.4	4	
	Avg	35.7	47.8	9	48.7	1.02	39.0	4	82
+78	Tran.	32.8	47.1	15	47.1				
	Tran.	33.0	46.6	14	47.0				
	Tran.				46.7				
	Tran.				46.5				
	Avg	32.9	46.9	15	46.8	1.00			
-100	Long.	36.5	48.7		50.3		39.5	5	
	Long.	36.6	49.0	15	50.2		39.9	5	
	Long.	36.7	48.9	15			39.0	5	
	Avg	36.6	48.9	15	50.3	1.03	39.5	5	81
-100	Tran.	32.4	47.7	15	47.4				
	Tran.	33.5	47.5	15	47.8	1.00			
-320	Long.	41.5	66.1	24	62.7		57.4	9	
	Long.	40.5	66.0	28	62.0		57.5	8	
	Long.	41.3	63.6		61.0		56.4	9	
	Long.	40.9	66.0	20			54.9	9	
	Long.	40.0	65.1	23			55.7	9	
	Avg	40.8	65.4	24	61.9	.95	56.4	9	86
-320	Tran.	37.2	61.6	27	54.7				
	Tran.	38.1	62.2	29	54.9				
	Tran.				55.1				
	Tran.				55.2				
	Avg	37.7	61.9	28	55.0	.89			
-423	Long.	46.7	96.7	31	75.0		75.9	11	
	Long.	47.7	96.5	31	68.8		76.3	11	
	Long.	46.6	92.7	27	70.3		74.1	11	
	Long.						74.9	11	
	Avg	47.0	95.3	30	71.4	.75	75.3	11	79
-423	Tran.	44.9	86.4	36	58.3				
	Tran.	43.4	84.9	24	58.4				
	Avg	44.2	85.7	30	58.4	.68			

*Heliarc butt weld; x-rayed; roll planished; no doubler reinforcement

TABLE XI

Mechanical Properties of 5086-H38 Aluminum Alloy

0.050" Sheet, Kaiser, Experimental Heat

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	el. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.	57.4	64.3	6	65.2	
	Long.	58.5	64.1	7	63.9	
	Long.	58.8	64.2	7	64.8	
	Ave.	58.2	64.2	7	64.6	1.01
+78°F	Trans.	56.5	65.8	9	69.0	
	Trans.	56.8	66.0	9		
	Ave.	56.7	65.9	9	69.0	1.05
-100°F	Long.	-	66.2	12	66.7	
	Long.	58.6	66.2	9	67.5	
	Long.	58.1	66.2	8	68.2	
	Ave.	58.4	66.2	10	67.5	1.02
-100°F	Trans.	58.4	67.7	10	71.9	
	Trans.	56.1	67.5	10		
	Ave.	57.3	67.6	10	71.9	1.06
-320°F	Long.	59.5	76.1	19	75.4	
	Long.	61.8	76.9	19	75.2	
	Long.	61.4	77.3	17	75.3	
	Ave.	60.9	76.8	18	75.3	0.98
-320°F	Trans.	68.3	81.6	17	80.0	
	Trans.	65.5	81.2	17		
	Ave.	66.9	81.4	17	80.0	0.98
-423°F	Long.	-	106	24	85.1	
	Long.	69.1	101	25	77.3	
	Long.	82.1	107	25	81.0	
	Ave.	75.6	105	25	81.1	0.77
-423°F	Trans.	65.5	92.4	25	85.3	
	Trans.	67.0	92.8	27		
	Ave.	66.3	92.6	26	85.3	0.92

TABLE XII

Mechanical Properties of 5154-H38 Aluminum Alloy

.040" Sheet, Alcoa, Heat No. 667-471

TEST TEMP °F	DIRECTION	F_{ty} ksi	F_{tu} ksi	e %	NOTCHED T.S. ksi (K_t=6.3)	NOTCHED/ UNNOTCHED TENSILE RATIO	HELIARC* BUTT WELD T.S. ksi	WELD ELONG %	JOINT EFF %
+78	Long.	40.0	47.8	9	49.7		33.9	3	
	Long.	40.2	47.7	9	49.5		36.6	3	
	Long.	40.4	47.4	9	49.5		35.6	2	
	Long.						36.7	3	
	Long.						35.1	3	
	Avg	40.2	47.6	9	49.5	1.04	35.7	3	75
+78	Tran.	40.6	49.2	15	54.0				
	Tran.	40.5	49.1	13	54.0				
	Avg	40.6	49.2	14	54.0	1.10			
-100	Long.	40.9	49.2	14	51.2		38.4	2	
	Long.	40.6	49.4	13	51.1		38.8	2	
	Avg	40.8	49.3	14	51.2	1.04	38.6	2	78
-100	Tran.	41.7	50.1	15	55.3				
	Tran.	40.9	50.3	15	55.4				
	Avg	41.3	50.2	15	55.4	1.21			
-320	Long	47.3	66.5	30	64.3		53.8	7	
	Long.	47.2	66.1	30	64.3		53.8	7	
	Long.	46.8	66.0	30	64.4		55.0	8	
	Long.						55.2	7	
	Long.						54.7	8	
	Avg	47.1	66.2	30	64.3	.97	55.5	7	84
-320	Tran.	47.0	63.8	29	66.0				
	Tran.	47.1	63.4	30	66.2				
	Avg	47.1	63.6	30	66.1	1.04			
-423	Long.	53.4	93.4	38	76.9		77.2	11	
	Long.	54.6	93.1	31	78.7		74.5	11	
	Long.	54.1	93.9	36	77.1		75.6	11	
	Avg	54.0	93.5	35	77.6	.83	75.8	11	81
-423	Tran.	57.0	88.0	37	76.5				
	Tran.	55.9	93.0	39	77.8				
	Avg	56.5	91.0	38	77.2	.85			

*Heliarc butt weld; roll planished; no doubler reinforcement

TABLE XIII

Mechanical Properties of 5456-H343 Aluminum Alloy

0.050" Sheet, Alcoa, Mil-A 19842

TEST TEMP. °F	DIRECTION	F_{ty} ksi	F_{tu} ksi	e %	NOTCHED T.S. ksi (K_t=6.3)	NOTCHED/ UNNOTCHED TENSILE RATIO	HELIARC* BUTT WELD T.S. ksi	WELD ELONG %	JOINT EFF %
+78	Long.	47.9	59.5	6.5	54.3		49.6	8.0	
	Long.	46.5	58.3	6.5	53.6		47.1	3.0	
	Long.	47.2	58.1	6.5	54.6		46.0	2.0	
	Avg	47.2	58.6	6.5	54.2	0.92	47.6	4.3	81
+78	Trans.	44.4	59.3	9.0	54.0		47.1	3.0	
	Trans.	46.3	61.5	8.5	51.6		47.6	3.0	
	Avg	45.4	60.4	8.7	52.8	0.87	47.4	3.0	78
-100	Long.	48.1	59.8	8.5	47.9		47.6	2.5	
	Long.	47.8	59.8	8.5	53.1		50.0	3.0	
	Long.	47.6	59.7	8.0			49.9	3.0	
	Avg	47.8	59.8	8.3	50.5	0.84	49.2	2.8	82
-100	Trans.	44.8	61.2	9.5	50.0		51.6	3.5	
	Trans.	46.1	61.2	9.0	46.4		52.1	4.0	
	Trans.				49.8				
	Avg	45.5	61.2	9.2	48.7	0.80	51.9	3.7	85
-320	Long.	53.2	72.4	8.0	50.9		67.1	8.0	
	Long.	52.9	73.0	8.5	47.9		67.6	8.5	
	Long.	52.9	72.6	8.0	49.8		69.8	10.5	
	Avg	53.0	72.7	8.2	49.5	0.68	68.2	9.0	94
-320	Trans.	51.1	70.9	7.0	47.7		69.8	8.5	
	Trans.	51.5	70.9	7.0	48.6		69.9	11.0	
	Avg	51.3	70.9	7.0	48.2	0.68	69.9	9.8	99
-423	Long.	60.7	84.3	7.0	54.8		79.5	6.5	
	Long.	60.1	81.6	5.0	53.9		75.8	5.5	
	Long.	60.3	84.7	6.0	56.5		76.6	6.0	
	Avg	60.4	83.5	6.0	55.1	0.66	77.3	6.0	93
-423	Trans.	59.7	80.5	4.0	49.6		82.8	5.5	
	Trans.	57.6	80.1	5.0	49.7		76.2	5.5	
	Avg	58.7	80.3	4.5	49.7	0.62	79.5	5.5	99

*Heliarc butt weld; x-rayed; roll planished; no doubler reinforcement

TABLE XIV

Mechanical Properties of 6061-T4 Aluminum Alloy

0.025" Sheet, Kaiser, QQ-A-327

TEST TEMP.	DIRECTION		F_{ty} ksi	F_{tu} ksi	el. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.		30.8	40.7	17	40.1	
	Long.		30.4	40.2	17	41.9	
	Long.		30.5	40.5	17		
		Ave.	30.6	40.5	17	41.0	1.01
+78°F	Trans.		26.1	39.4	17	38.4	
	Trans.		26.5	39.9	17	38.9	
	Trans.					40.5	
		Ave.	26.3	39.7	17	39.3	0.99
-100°F	Long.		32.4	44.5	20	43.0	
	Long.		31.5	43.6	20	42.1	
	Long.		32.1	44.5	21	42.2	
		Ave.	32.0	44.2	20	42.4	0.96
-100°F	Trans.		29.0	43.7	22	42.3	
	Trans.		29.1	43.3	20	41.2	
		Ave.	29.1	43.5	21	41.8	0.96
-320°F	Long.		37.6	58.0	28	50.0	
	Long.		37.6	57.9	30	51.7	
	Long.		37.2	58.1	28	51.9	
		Ave.	37.5	58.0	29	51.2	0.88
-320°F	Trans.		33.1	57.2	30	50.5	
	Trans.		31.4	56.5	28	51.7	
		Ave.	32.3	56.9	29	51.1	0.90
-423°F	Long.		48.4	87.1	32	61.7	
	Long.		46.4	86.6	31	61.3	
	Long.		46.8	86.6	31	63.1	
		Ave.	47.2	86.8	32	62.0	0.72
-423°F	Trans.		44.4	92.5	34	62.0	
	Trans.		42.8	92.1	34	63.1	
		Ave.	43.6	92.3	34	62.6	0.68

TABLE XVI

Mechanical Properties of 6061-T6 Aluminum Alloy

0.020" Sheet, Kaiser, QQ-A-327

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	el. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.	43.8	47.9	11	49.2	
	Long.	43.4	47.2	11	49.5	
	Long.	43.4	47.2	10	50.1	
	Ave.	43.5	47.4	11	49.6	1.05
+78°F	Trans.	41.6	46.4	10	48.0	
	Trans.	41.6	46.4	10	49.0	
	Ave.	41.6	46.4	10	48.5	1.05
-100°F	Long.	45.1	51.5	11	53.2	
	Long.	45.7	51.7	11	53.8	
	Long.	45.9	51.8	11	53.5	
	Ave.	45.6	51.7	11	53.5	1.04
-100°F	Trans.	44.4	51.0	11	51.6	
	Trans.	44.6	51.5	11	51.6	
	Ave.	44.5	51.3	11	51.6	1.01
-320°F	Long.	51.4	62.1	17	61.6	
	Long.	50.7	61.4	12	61.9	
	Long.	51.7	62.9	17	63.3	
	Long.	50.9	62.6	17		
	Ave.	51.2	62.3	16	62.3	1.00
-320°F	Trans.	47.2	60.9	12	60.1	
	Trans.	49.0	61.2	17	53.9	
	Trans.	49.2	60.6	18	59.6	
	Trans.				59.5	
	Ave.	48.5	60.9	16	58.3	0.96
-423°F	Long.	56.1	79.0	24	72.7	
	Long.	54.0	82.7	25	75.3	
	Long.	54.6	77.6	25	77.3	
	Long.	-	81.1	19	73.0	
	Ave.	54.9	80.1	23	74.6	0.93
-423°F	Trans.	55.0	77.9	25	71.3	
	Trans.	-	71.0	25	70.2	
	Trans.	54.7	78.3	25		
	Ave.	54.9	75.7	25	70.8	0.94

TABLE XVI

Mechanical Properties of 6061-T6 Aluminum Alloy

1" Plate, Kaiser, QQ-A-327

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	el. %	R.A. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.	44.1	48.4	20	31	70.3	
	Long.	44.1	48.1	19	35	70.2	
	Long.	43.8	47.8	19	47	70.6	
	Ave.	44.0	48.1	19	38	70.4	1.46
+78°F	Trans.	71.6	81.2	10	9	71.1	
	Trans.	71.4	81.5	10	11	65.8	
	Ave.	71.5	81.4	10	10	68.5	0.84
-100°F	Long.	46.4	52.2	21	45	76.2	
	Long.	47.1	52.9	21	43	75.3	
	Long.	-	52.5	22	43	75.6	
	Ave.	46.8	52.5	21	44	75.7	1.44
-100°F	Trans.	73.0	84.7	6	6	75.6	
	Trans.	76.8	84.7	6	6	75.3	
	Ave.	74.9	84.7	6	6	75.5	0.89
-320°F	Long.	-	63.8	25	46	86.0	
	Long.	52.1	64.3	25	37	85.9	
	Long.	52.4	64.4	24	37	86.2	
	Ave.	52.3	64.2	25	40	86.0	1.34
-320°F	Trans.	83.7	94.0	4	3	86.9	
	Trans.	81.7	89.7	2	4	75.4	
	Ave.	82.7	91.9	3	4	81.2	0.88
-423°F	Long.	54.8	79.8	29	39	96.1	
	Long.	56.5	81.1	28	33	98.0	
	Long.	56.0	79.9	29	40	95.7	
	Ave.	55.8	80.3	29	37	96.6	1.20
-423°F	Trans.	94.6	102	3	2	94.6	
	Trans.	95.5	102	3	2	88.2	
	Ave.	95.1	102	3	2	91.4	0.90

TABLE XVII

Mechanical Properties of 7075-T6 Aluminum Alloy

0.025" Sheet, Alcoa, QQ-A-283

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	el. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°	Long.	71.8	79.8	9	80.6	
	Long.	68.9	79.0	9	82.2	
	Long.	-	79.8	9	81.4	
	Ave.	70.4	79.5	9	81.4	1.02
+78°F	Trans.	69.4	77.7	10	77.9	
	Trans.	69.4	77.4	10	77.2	
	Ave.	69.4	77.6	10	77.6	1.00
-100°F	Long.	75.7	84.3	10	84.6	
	Long.	76.7	85.3	10	83.7	
	Long.	76.2	85.6	11	85.5	
	Ave.	76.2	85.1	10	84.6	0.99
-100°F	Trans.	74.0	82.7	11	80.5	
	Trans.	74.2	83.7	7	80.7	
	Ave.	74.1	83.2	9	80.6	0.97
-320°F	Long.	86.5	97.2	10	76.0	
	Long.	86.5	97.2	10	72.9	
	Long.				78.2	
	Ave.	86.5	97.2	10	75.7	0.78
-320°F	Trans.	81.6	94.7	11	74.3	
	Trans.	82.0	95.1	12	73.5	
	Ave.	81.8	94.9	12	73.9	0.78
-423°F	Long.	98.3	116	8	83.7	
	Long.	106	117	6	84.2	
	Long.	95.7	114	9	85.0	
	Ave.	100	116	8	84.3	0.73
-423°F	Trans.	96.6	111	11	79.1	
	Trans.	-	112	13	78.3	
	Ave.	96.6	112	12	78.7	0.70

TABLE XVIII

Mechanical Properties of 7075-T6 Aluminum Alloy

2.5" Plate, Kaiser, QQ-A-283

TEST TEMP °F	DIRECTION	F_{ty} ksi	F_{tu} ksi	e %	R. A. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.	84.7	92.9	14	13	115	1.24
	Trans.	42.2	47.0	11	43	68.7	1.46
-100°F	Long.	84.4	98.5	8		116	1.18
-320°F	Long.	106	110	4	4	112	1.02
	Trans.	49.9	61.9	26	36	86.2	1.39
-423°F	Long.	114	129	6	8	116	0.90

TABLE XIX

Mechanical Properties of 7079-T6 Aluminum Alloy

.080" Sheet, Kaiser

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	el. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.	68.8	76.7	12	83.8	
	Long.	68.9	76.9	11	82.5	
	Long.	69.1	77.6	11		
	Ave.	68.9	77.1	11	83.2	1.08
+78°F	Trans.	66.7	75.9	10	81.3	
	Trans.	66.6	76.0	11	81.1	
	Ave.	66.7	76.0	11	81.2	1.07
-100°F	Long.	72.9	81.4	12	85.6	
	Long.	73.1	81.9	12	83.7	
	Long.	73.5	81.3	13		
	Ave.	73.2	81.5	12	84.7	1.04
-100°F	Trans.	69.9	80.9	12	84.5	
	Trans.	69.4	81.0	12	83.4	
	Ave.	69.7	81.0	12	84.0	1.04
-320°F	Long.	82.0	94.5	15	91.3	
	Long.	82.4	94.3	16	91.0	
	Long.	81.8	94.2	16		
	Ave.	82.1	94.3	16	91.2	0.97
-320°F	Trans.	78.2	94.0	11	80.1	
	Trans.	79.1	93.6	13	84.0	
	Ave.	78.7	93.8	12	82.1	0.88
-423°F	Long.	90.9	112	8	81.2	
	Long.	90.8	110	8	76.0	
	Long.	91.6	113	7		
	Ave.	91.1	112	8	78.6	0.70
-423°F	Trans.	89.4	105	6	78.5	
	Trans.	91.6	120	6	77.1	
	Ave.	90.5	113	6	77.8	0.69

TABLE XXI

Mechanical Properties of 7079-T6 Alloy

5" Billet, Aluminum Company of America, 0-01041

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	el. %	R.A. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.	70.8	77.9	11	17	91.1	
	Long.	66.5	74.7	10	17	97.0	
	Long.	70.9	77.9	12	16	94.0	
	Long.	64.0	73.7	12	17	96.5	
	Long.	71.6	78.6	10	11	87.3	
	Long.	64.2	73.9	12	11	97.5	
	Long.					87.9	
	Ave.	68.0	76.1	11	15	93.0	1.22
+78°F	Trans.	68.1	77.6	7	11	87.2	
	Trans.	63.1	73.1	8	12	89.3	
	Trans.	63.9	75.7	7	9	90.3	
	Trans.	62.9	74.2	10	8	89.9	
	Ave.	64.5	75.2	8	10	89.2	1.19
-100°F	Long.	71.5	79.6	3	8	84.8	
	Long.	69.2	78.1	4	8	88.3	
	Long.	71.3	78.4	3	8	83.2	
	Long.	68.9	78.5	4	9	80.6	
	Ave.	70.2	78.7	4	8	84.2	1.07
-100°F	Trans.	66.0	77.2	5	9	79.9	
	Trans.	68.5	73.8	3	8	72.6	
	Ave.	67.3	75.5	4	9	76.3	1.01
-320°F	Long.	-	85.5	-	2	78.2	
	Long.	79.2	87.1	2	4	68.1	
	Long.	85.4	89.3	4	2	77.6	
	Long.	84.1	89.3	3	3	83.2	
	Long.	85.9	87.8	3	2	71.5	
	Long.	-	87.9	3	2	79.0	
	Long.	84.0	90.0	3	2	77.1	
	Long.	85.4	88.5	2	3	71.6	
	Ave.	84.0	88.2	3	3	75.8	0.86
-320°F	Trans.	71.3	83.6	2	2	68.7	
	Trans.	77.1	82.4	2	1	63.1	
	Trans.	73.8	82.0	4	3	77.6	
	Trans.					70.3	
	Ave.	74.1	82.7	3	2	69.9	0.85
-423°F	Long.	80.7	91.5	3	3	74.9	
	Long.	90.8	98.2	2	4	69.7	
	Long.	-	90.1	1	3	59.4	
	Long.	91.1	97.8	3	3	48.5	
	Long.					70.4	
	Ave.	87.5	94.4	2	3	64.6	0.68
-423°F	Trans.	88.3	92.4	1	2	51.4	
	Trans.	90.5	91.1	1	2	58.3	
	Ave.	89.4	91.8	1	2	54.9	0.60

TABLE XXI

Mechanical Properties of 7178-T6 Aluminum Alloy

0.036" Sheet, Kaiser, MIL-A-9180A

TEST TEMP.	DIRECTION	F_{ty} ksi	F_{tu} ksi	el. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.	82.4	90.2	12	91.4	
	Long.	82.6	89.6	12	93.3	
	Long.	83.0	90.0	12	90.7	
	Ave.	82.7	89.9	12	91.8	1.02
+78°F	Trans.	79.9	90.2	11	79.5	
	Trans.	80.1	90.5	11	88.5	
	Ave.	80.0	90.4	11	84.0	0.93
-100°F	Long.	87.8	95.3	11	81.0	
	Long.	88.2	95.2	11	75.0	
	Long.	87.5	95.0	11	74.5	
	Ave.	87.8	95.2	11	76.8	0.81
-100°F	Trans.	82.8	95.4	10	81.9	
	Trans.	84.1	95.9	10	66.4	
	Trans.				74.5	
	Ave.	83.5	95.7	10	74.3	0.78
-320°F	Long.	98.6	106	4	59.5	
	Long.	98.9	106	4	57.2	
	Long.	98.8	107	5	51.9	
	Long.				61.8	
	Ave.	98.8	106	4	57.6	0.54
-320°F	Trans.	94.5	106	3	55.4	
	Trans.	92.2	106	3	54.3	
	Trans.				46.0	
	Ave.	93.4	106	3	51.9	0.49
-423°F	Long.	112	122	2	68.3	
	Long.	114	125	2	57.5	
	Long.	108	122	2	61.2	
	Long.	111	122	3	63.9	
	Ave.	111	123	2	62.7	0.51
-423°F	Trans.	112	125	3	56.9	
	Trans.	111	123	3	54.1	
	Trans.				59.1	
	Ave.	112	124	3	56.7	0.46

TABLE XXII

Mechanical Properties of X7275-T6 Aluminum Alloy

0.050" Sheet, Kaiser, Experimental Heat

TEST TEMP.	DIRECTION		F_{ty} ksi	F_{tu} ksi	el. %	NOTCHED T.S. (K_t=6.3) ksi	NOTCHED/UNNOTCHED TENSILE RATIO
+78°F	Long.		75.7	87.0	14	90.9	
	Long.		75.1	86.0	14	90.7	
	Long.		76.5	86.6	14	91.3	
		Ave.	75.8	86.5	14	91.0	1.05
+78°F	Trans.		72.4	83.7	14	89.7	
	Trans.		72.7	83.4	14	89.5	
		Ave.	72.6	83.6	14	89.6	1.07
-100°F	Long.		75.5	86.4	15	95.4	
	Long.		76.2	84.5	15	95.7	
	Long.		75.2	84.7	15	94.6	
		Ave.	75.6	85.2	15	95.2	1.12
-100°F	Trans.		71.9	83.2	14	89.8	
	Trans.		74.7	84.1	14	91.4	
		Ave.	73.3	83.7	14	90.6	1.08
-320°F	Long.		86.1	95.0	7	87.4	
	Long.		87.5	99.4	5	76.6	
	Long.		81.1	94.6	6	71.9	
		Ave.	84.9	96.3	6	78.6	0.82
-320°F	Trans.		76.5	93.3	11	79.1	
	Trans.		83.7	99.1	6	84.7	
		Ave.	80.1	96.2	9	81.9	0.85
-423°F	Long.		97.9	116	5	76.1	
	Long.		98.9	111	4	75.0	
	Long.					74.8	
		Ave.	98.4	114	5	75.3	0.67
-423°F	Trans.		93.5	106	4	81.2	
	Trans.		96.8	109	4	82.0	
		Ave.	95.2	108	4	81.6	0.76

TABLE XXIII

Material Selection Guide

(An X Indicates the Material May Be Used For Structural Applications at the Indicated Temperature)

Material	Temperature			
	+78°F	-100°F	-320°F	-423°F
2014-T6 Sheet	X	X	X	X
2024-T3 Sheet	X	X	X	
2024-T4 Sheet	X	X	X	X
2024-T4 Plate	X	X	X	X
2219-T81 Sheet	X	X	X	X
2219-T87 Sheet	X	X	X	X
5052-H38 Sheet	X	X	X	X
5083-H38 Sheet	X	X	X	X
5086-H34 Sheet	X	X	X	
5086-H38 Sheet	X	X	X	
5154-H38 Sheet	X	X	X	
5456-H343 Sheet	X	X		
6061-T4 Sheet	X	X	X	
6061-T6 Sheet	X	X	X	X
6061-T6 Plate	X	X	X	X
7075-T6 Sheet	X	X		
7075-T6 Plate	X	X		
7079-T6 Sheet	X	X	X	
7079-T6 Billet	X	X		
7178-T6 Sheet	X			
7275-T6 Sheet	X	X		

REFERENCES:

1. Mc Clintock, R. M., and Gibbons, H. P., "A Compilation of Mechanical Properties of Materials at Cryogenic Temperatures," NBS Rep. 6064, July 1, 1959.

2. Fontana, M. G., et al., "Investigation of Mechanical Properties and Physical Metallurgy of Aircraft Alloys at Very Low Temperatures," AF Tech. Rep. No. 5662, Parts 1, 3 and 5, Jan. 1948 and Dec. 1953.

3. McGee, R. L., Campbell, J. E., Carlson, R. L., and Manning, G. K., "How Low Temperatures Affect Nine High-Strength Alloys," Materials in Design Eng., Nov. 1959, pp. 106-107.

4. Hanson, M. P., Stickley, G. W., and Richards, H. T., "Sharp Notch Behavior of Some High-Strength Sheet Aluminum Alloys and Welded Joints at 75°, -320°, and -423°F," Paper presented at annual meeting ASTM, Atlantic City, June 1960.

5. Special Astm Committee, "Fracture Testing of High-Strength Sheet Materials," Chapter 1, ASTM Bulletin, Feb. 1960.

6. Low, J. R., "The Relation of Microstructure to Brittle Fracture," Relation of Properties to Microstructure, American Society for Metals, Cleveland, Ohio, 1954, p. 163.

7. Parker, E. R., "Modern Concepts of Flow and Fracture," Trans. ASTM, 50, 1958, p. 52.

8. Hurlich, A., Tanalski, T. T., Watson, J. F., and Christian, J. L., Unpublished data, Convair-Astronautics.

9. Watson, J. F., and Christian, J. L., "Cryostat and Accessories for Tensile Testing at -423°F," to be published in Bulletin, ASTM.

10. Lorig, C. H., "Influence of Metallurgical Factors," Behavior of Metals at Low Temperatures, ASM, Cleveland, 1953, pp. 71-105.

11. Low, J. R. Jr., "The Influence of Mechanical Variables," Behavior of Metals at Low Temperatures, ASM, Cleveland, 1953, pp. 39-70.

12. Christian, J. L., and Watson, J. F., "Properties of 7000 Series Aluminum Alloys at Cryogenic Temperatures", Presented at Sixth National Cryogenic Engineering Conference, Boulder, Colorado, Sept. 1960.

4 October 1960

SUBJECT: Mechanical Properties of Cold-Rolled Commercially Pure Titanium Sheet, AMS 4901 (Ti-75A)

ABSTRACT: Standard and notched tensile tests were conducted at +78°, -60°, -320°, and -423°F in both longitudinal and transverse directions on samples from a 0.012" thick sheet of AMS 4901 which had been cold rolled approximately 30%. The material exhibited promising properties at room temperature (120 ksi F_{ty}, 135-140 ksi F_{tu}, 5% elongation, and notched/unnotched tensile ratios in excess of unity); but tests at all sub-zero temperatures demonstrated notch sensitivity which increased with decreasing temperature.

While the strength of commercially pure titanium (AMS 4901) can be significantly increased by cold working, such material is not recommended for cryogenic temperature applications. It would be of interest to determine the low temperature properties of higher purity unalloyed titanium (AMS 4900 and AMS 4902) in the cold rolled condition.

Prepared by J. E. Chafey
J. E. Chafey

Approved by A. Hurlich
A. Hurlich
Research Group Engineer
Materials Research Group

AH:JEC:jfd

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TO: Distribution

FROM: Materials Research Group, 592-1

SUBJECT: Mechanical Properties of Cold-Rolled Commercially Pure Titanium Sheet, AMS 4901 (Ti-75A)

INTRODUCTION:

The applicability of certain titanium alloys for use in experimental thin-skinned tanks to contain cryogenic propellants is limited by the fact that these alloys cannot be commercially produced in gages below approximately 0.025" in thickness, whereas some projected tank designs consider the utilization of 0.010" gages. The 5Al-2.5 Sn-Ti alloy, for example, has been demonstrated to possess excellent combinations of strength, ductility, fracture resistance, and good welded joint properties at temperatures down to -423°F, but has been produced in thicknesses below approximately 0.020" only by chemical milling processes which often result in poor surface condition, poor thickness control, and may lead to hydrogen embrittlement.

Unalloyed titanium in the annealed condition has good ductility and impact resistance at extreme sub-zero temperatures[1] and can be rolled in wide sheet form down to foil gages. The Titanium Metals Corporation of America, suggested that cold-rolled-to-strength thin gage unalloyed titanium be evaluated for possible substitution for the 5Al-2.5 Sn-Ti alloy in cryogenic applications inasmuch as the strength of the latter alloy could be readily matched by cold working the unalloyed material, and furthermore, cold rolling of titanium sheet in the Sendzimir mill would develop superior surface condition and permit 1/2 AISI thickness tolerance control.

T.M.C.A. accordingly submitted a 0.012" thick sheet, 32" X 22" in size, which had been cold reduced from 0.017" (29.4% reduction), Heat No. M9656, AMS 4901, Ti-75A, commercial purity unalloyed titanium. The supplier furnished the following test data:

Longitudinal - F_{ty}-123.0 ksi, F_{tu}-143.0 ksi, Elongation -6%
Transverse - F_{ty}-124.0 ksi, F_{tu}-152.0 ksi, Elongation -6%

DATA AND DISCUSSION:

Standard and edge-notched tensile test specimens, CV-A drawings EMG-D-1 and MRG-D-10 respectively, were taken in both longitudinal and transverse directions and were tested at +78°, -60°, -320°, and -423°F. The small size

1. Memorandum on Mechanical Properties of Titanium and Other Materials at Very Low Temperatures" April 25, 1957, Titanium Metallurgical Laboratory, Battelle Memorial Institute.

of the sheet permitted no more than duplicate test specimens to be tested under any condition. The results of the tests are presented in Table I. Yield strengths were not determined at most of the sub-zero temperatures because of a malfunction of the extensometer.

The room temperature mechanical properties are somewhat lower than reported by the manufacturer but the strength is higher than usually obtained in the 5Al-2.5 Sn-Ti alloy and the ductility is lower. The notched/unnotched tensile ratio is in the range of 1.06-1.13, which, while above unity, is nevertheless below the level of 1.30-1.35 observed in the annealed 5Al-2.5 Sn-Ti alloy.

At sub-zero testing temperatures, the ductility decreases with decreasing temperature to values of 1.0-1.5% elongation at -423°F. The notched/unnotched tensile ratio, a much more meaningful criterion of brittle fracture susceptibility, decreases rapidly with decreasing temperature; being 0.95 at -60°F, 0.73 at -320°F, and 0.54 at -423°F in the longitudinal direction and lower in the transverse direction. Annealed 5Al-2.5 Sn-Ti alloy, 040" in thickness shows a notched/unnotched tensile ratio of 1.22 at -100°F, 1.15 at -220°F, and 0.97 at -423°F in the longitudinal direction, considerably higher values than obtained with the cold rolled unalloyed titanium sheet.

Based upon these results, cold rolled-to-strength unalloyed titanium sheet made to AMS 4901 cannot be recommended for cryogenic temperature applications because of its high notch sensitivity and tendency to brittle fracture at sub-zero temperatures.

Very high purity unalloyed titanium has a yield strength in the range of 10,000-20,000 psi. "Commercially pure" unalloyed titanium contains varying amounts of carbon, oxygen, iron, hydrogen and other impurities which increase its hardness and strength to considerably higher levels. "Commercially pure" unalloyed titanium is currently available in three grades as follows:

Grade Designation	AMS 4900	AMS 4901	AMS 4902
Minimum yield strength, psi	55,000	70,000	40,000
Carbon, Max. %	0.20	0.20	0.20
Hydrogen, Max. %	0.015	0.015	0.015
Other elements, total %	0.6	0.8	0.6

The AMS 4901 grade contains the highest level of total impurity content and has the highest strength of the three grades of unalloyed titanium. While the impurities increase the strength of titanium, they also decrease the ductility and increase the tendency toward brittle fracture, and this effect becomes more pronounced at lower testing temperatures. It would be of interest to evaluate the properties of cold rolled-to-strength AMS 4900 and AMS 4902 at sub-zero temperatures. The lower impurity contents of these materials may enhance their resistance to brittle fracture at sub-zero temperatures.

CONCLUSION:

1. 30% cold rolled unalloyed titanium (AMS 4901) sheet has promising room temperature mechanical properties, but demonstrates notch sensitivity which increases with decreasing temperatures in the range of -60° to -423°F.

2. Cold rolled-to-strength unalloyed titanium (AMS 4901) is not recommended for cryogenic temperature applications.

3. It would be of interest to evaluate the sub-zerotemperature mechanical properties of higher purity cold rolled-to-strength unalloyed titanium sheet (AMS 4900 and AMS 4902).

TABLE I

Mechanical Properties of Cold Rolled Commercially Pure Titanium Alloy Sheet
AMS 4901, TMCA Heat No. 9656 Cold Rolled 29.4% to 0.012" Thickness

TEST TEMP. °F	GRAIN DIRECTIONS	YIELD STRENGTH ksi	ULTIMATE TENSILE ksi	ELONG. %	NOTCHED TENSILE STRENGTH K_t=6.3 ksi	NOTCHED/ UNNOTCHED TENSILE RATIO
+78	Longitudinal	120.6	137.8	5.2	149.1	
	Longitudinal	120.7	136.6	5.2	140.9	
	Ave.	120.6	137.2	5.2	145.0	1.06
+78	Transverse	121.7	144.5	5.5	165.4	
	Transverse	121.6	147.4	5.2	163.4	
	Ave.	121.6	146.0	5.3	164.4	1.13
-60	Longitudinal	—	153.7	-	145.3	
	Longitudinal				147.4	
	Ave.				146.3	0.95
-60	Transverse	—	171.0	-	117.4	
	Transverse		172.3			
	Ave.		171.7			0.68
-320	Longitudinal	--	210.6	5.0	150.8	
	Longitudinal		212.3	5.5	155.4	
	Ave.		211.5	5.3	153.1	0.73
-320	Transverse	—	210.3	2.5	122.4	
	Transverse		212.3	2.5	136.8	
	Ave.		211.3	2.5	129.6	0.61
-423	Longitudinal	217.1	233.1	1.5	128.0	
	Longitudinal	—	240.5	-	129.9	
	Longitudinal	—	228.0	-	122.0	
	Ave.		233.9		126.6	0.54
-423	Transverse	—	237.4	1.0	121.2	
	Transverse	—	241.1	1.0	124.6	
	Ave.		239.2	1.0	122.9	0.51

4 October 1960

TO: Distribution

FROM: Materials Research Group, 592-1

SUBJECT: Addendum I - MRG-191 "Mechanical Properties of Commercially Pure Titanium Sheet, AMS 4901 (Ti-75A)"

Tensile Test of Welded-Joint on 38" Specimen

Subsequent to the date that the notched and unnotched tensile test data for the subject material was summarized, as shown in Table I, one additional test was conducted on this sheet. This consisted of a static tensile test at room temperature on a welded-joint specimen conforming to CV-A Drawing No. 7-07781-823. The specimen width was 3.50" in the 16" long test section. The overall length of the specimen was 38". The joint was located at the center of the specimen and consisted of a Heliarc fusion butt weld plus a spot welded doubler of the same 0.012" thick cold-rolled titanium sheet. The doubler was attached by four rows of resistance spot welds on each side of the butt weld. The butt weld was roll-planished prior to attaching the doubler. The rolling direction of the sheet was parallel to the testing direction for both the specimens and the doubler. The material available was sufficient to prepare only one specimen.

The ultimate strength of the specimen, as determined by a static tensile test at +78°F, was 131,500 psi. Fracture occurred immediately adjacent to the fourth row of spot welds.

As noted in Table I, the ultimate strength of the unwelded sheet in the longitudinal direction was 137,200 psi, average. Hence, the joint efficiency on the basis of the test performed is 131,500/137,200 X 100 = 96%.

Prepared by J. E. Chafey
J. E. Chafey

Approved by [signature] for
A. Hurlich
Research Group Engineer
Materials Research Group

AH:JEC:jfd

Distribution:

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J. Fager	541-1	T. Sullins	597-3

CONVAIR ASTRONAUTICS

REPORT MRG-209
PAGE 1
13 January 1961

SUBJECT: Materials Selection for the Rift Vehicle

ABSTRACT: The materials problems arising from the nuclear radiation environment associated with the Rift vehicle have been studied in reference to primary structural alloys; organic materials including plastics, thermal and electrical insulations, lubricants, hydraulic fluids, sealants, and coatings; and electronic devices, including semiconductors. It was concluded that a number of new materials problems concerning structural alloys will require study in support of the Rift program, but that the current state of the art will supply adequate design data in the fields of organic materials and electronic devices. The materials problems include: the effects of radiation on structural alloys at cryogenic temperatures (This study is already in progress on a company sponsored program); the inter-relation of alloy content, induced radioactivity, and mechanical properties; and the effect of nuclear radiation on solid state diffusion and phase transformations.

Four alloys were chosen for study as possible primary structural alloys for the Rift vehicle; namely Type 301 stainless steel cold-rolled 60 percent, Type 310 stainless steel cold-rolled 75 percent, 2014-T6 aluminum, and A110AT titanium. Important factors considered during the study included induced radioactivity, high temperature properties (of importance during re-entry), susceptibility to radiation damage, and the more usual factors such as strength/density ratios, toughness (i.e., resistance to brittle fracture), weldability, adequate mechanical properties between -423°F and moderately high temperatures, corrosion resistance and formability. Based on these factors, Type 310 stainless steel cold-rolled 75 percent was selected as the preferred primary structural alloy for the Rift vehicle. Type 301 stainless steel was felt to be of marginal toughness due to the combined environments of low temperature, high tensile stress, and neutron flux, all of which are known to promote the embrittling austenite to martensite phase transformation. The 2014-T6 aluminum was not selected due to the marginal toughness of its welded joints, and its poor high temperature properties (limited to 250°F), although this alloy does have exceptionally low induced radioactivity. The A110AT was regarded as an excellent material for design optimization at a later date, but was not selected at the present time due to the wider background knowledge available for the cold worked stainless steel.

Prepared by: J. F. Watson
J. F. Watson

Approved by: A. Hurlich
A. Hurlich
Research Group Engineer
Materials Research Group

AH:JFW:jml:vea

FORM NO. A-702-1

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D. H. Robey, 593-1

TO: N. O'Rourke, 581-1

FROM: Materials Research Group, 592-1

SUBJECT: Materials Selection for the Rift Vehicle

The selection of engineering materials for application in the Rift vehicle involves not only the consideration of the wide spectrum of environmental conditions experienced by "conventional" missiles and space vehicles, but in addition involves the added consideration of the effects of nuclear radiation on materials. All of the "conventional" materials problems involved in the use of a wide variety of structural metals, plastics, and thermal insulations under conditions of high and low temperature, fatigue, corrosion, and other environmental factors peculiar to space which include low pressure with resultant lubrication and evaporation problems, radiation (ultraviolet, electron, and proton) and erosion due to micrometeorites and molecular impacts have been encountered at Convair-Astronautics during the Atlas (1955-) and Centaur (1959-) programs and have either been solved or are currently under study. Consequently, the emphasis in this study is placed on the more recent problem of radiation damage in materials, particularly that damage occurring at low temperature. The other problems mentioned above will be discussed only insofar as they pertain to the overall materials selection for the Rift vehicle, but the reader is directed to the references listed in the bibliography for detailed discussions of the materials problems involved in systems such as Atlas and Centaur which do in fact also pertain to the Rift study as well. (1, 2, 3).

The nature of the radiation environment experienced by the Rift vehicle indicates that materials selection must be considered separately for those materials prone to neutron damage; notably metals and structural alloys, electronic devices including semiconductors, and ceramics; and those materials susceptible to gamma damage; especially plastics, thermal and electrical insulations, lubricants, hydraulic fluids, sealants, and coatings.

STRUCTURAL ALLOYS

A wide variety of high strength sheet materials including cold-rolled austenitic stainless steels; aluminum, titanium, nickel, and cobalt base alloys; as well as several heat treatable stainless steels have been subjected at Convair-Astronautics to tests at temperatures ranging down to -423°F to determine their suitability for application in missile and space vehicle systems. These programs were supported in part by the Air Force Atlas and Centaur contracts, but the greater portion was supported by internal company funding which had been allocated to advanced research and development projects. The above alloys were selected for study because they exhibited one or more of the following characteristics: high strength/density ratios; good toughness (i.e., resistance to brittle fracture); adequate weldability; retention of properties at both cryogenic temperatures and moderately high temperatures in the range of 700°F

to 1200°F; corrosion resistance; and good formability. In order to obtain optimum strengths levels, the alloys selected for study were either cold worked (cold-rolled) or heat treated (age hardened or quenched and tempered) to their highest strength levels commensurate with adequate toughness. In addition, since weldability is of prime importance in the fabrication of these vehicles, alloys were tested in both the base metal and heliarc butt-welded configurations.

The alloys were subjected to tensile testing at 78°F, -100°F, -320°F, and -423°F in both smooth and notched configurations, to yield values of yield strength, tensile strength, elongation, and notched/unnotched tensile ratios (stress concentration factor, (K_t=6.3) in the base metal, and tensile strength and elongation in heliarc butt-welded joints.

The notched tensile tests were included for study to evaluate toughness, which is a measure of resistance to catastrophic brittle fracture. Toughness is a property of vital importance to the missile designer because his structures are subject to shock type loads which occur during hydraulic hammering, vibration due to rocket engine firing, action of quick-closing valves, etc., and will contain built in stress concentrations of varying degrees of intensity due to welding defects, tool marks, assembly eccentricities, random defects in the metal, etc. These conditions all favor brittle failure, and become even more severe at low temperature in that brittle fracture of many materials is more prone to occur at reduced temperatures.

As a result of these studies, four alloys were selected as candidate primary structural alloys for the Rift vehicle and they are; Type 310 stainless steel cold-rolled 75 percent, Type 301 stainless steel cold-rolled 60 percent, 2014-T6 aluminum,and A110AT titanium. The mechanical properties and chemical composition of these alloys are summarized in Tables I, II and III. As a result of the considerations given in the following discussion, the alloy selected for primary structure was Type 310 stainless steel cold-rolled 75 percent. Before making a detailed analysis of each alloy system, several general points will be discussed in relation to each of the alloy systems.

One important new materials problem resulting from the Rift flight profile is the effect of nuclear radiation on structural alloys at -423°F. With the introduction of nuclear powered upper stage space vehicles using liquid hydrogen as a working fluid, the problem of radiation damage to structural materials at -423°F assumes major significance. The reason for this concern has to do with the nature of radiation damage as a function of temperature. At ambient (70°F) and elevated temperatures, radiation damage tends to be "self-healing", in that radiation induced lattice defects anneal out, leaving a relatively undamaged metal lattice. At cryogenic temperatures, however, these radiation induced defects are "frozen" into the lattice, and result in much more severe embrittlement affects. To date, however, no quantitative studies have been performed to determine the magnitude of this effect. Convair, which has been actively interested in nuclear powered upper stage vehicles such as the RIFT program, nuclear recoverable boosters, and other associated programs, foresees the urgent need for data describing the effects of nuclear radiation on high-strength aerospace vehicle

materials at -423°F, and has initiated company sponsored experimental programs to measure this phenomenon.

Investigations of the nature of radiation damage occurring in metals at cryogenic temperatures have been limited to studies of pure single crystals at liquid helium temperatures. Most of these studies have measured changes in electrical resistivity as a function of integrated neutron flux. (Resistivity, a physical property, bears no relation to mechanical properties such as yield and tensile strength, which are of primary interest in the design of space vehicles). No work has been done on low temperature radiation effects in the high strength structural alloys which will be used in nuclear powered space vehicles.

One recent paper by Blewitt and associates dealing with the effects of radiation on copper single crystals at 15°K shows that a dose of 1.6×10^{17} thermal neutrons results in a fourfold increase in yield strength (4). Such a large increase leads to the suspicion that embrittlement may be occurring under these conditions, and certainly implies that further work is needed in this area.

In another study wherein samples were irradiated at 70°F, and then tested at low temperature, Type 347 stainless steel was subjected to a neutron flux of 5×10^{21} nvt (about 10^4 greater than that expected in RIFT). This steel exhibited a Charpy V-Notch impact strength of 120 ft-lb at 70°F before irradiation and 55 ft-lb at 70°F after irradiation, and 19 ft-lb after irradiation (at 70°F) when tested at -320°F. Thus, the room temperature toughness decreased sharply, and in addition, a ductile-brittle transition has appeared, which is not characteristic of face centered cubic materials such as 437 stainless steel.

Finally, Convair has also investigated the work being done under NASA contract (NASw-114) entitled "Effect of Nuclear Radiation on Materials at Cryogenic Temperatures", and feels that the Convair program will yield additional pertinent engineering data at an early date (March, 1961).

Convair-Astronautics has been active in the cryogenic field as a result of work in the Atlas and Centaur programs. The Atlas program introduced a broad spectrum of cryogenic materials problems at liquid oxygen temperature (-297°F), and the Centaur program extended the same problems to the boiling point of liquid hydrogen (-423°F).

This work has involved the staffing and equipping of complete cryogenic laboratories designed especially for studies of aerospace vehicle materials including high strength structural alloys of stainless steel, aluminum, titanium, and many others; thermal insulations; seals, bearings, and gasket materials; and all other materials used in these vehicles at cryogenic temperatures.

The studies of the high strength alloys were oriented toward space vehicle application so that in addition to determinations of base metal mechanical properties, the properties of welded joints were studied, and in addition, various indices of toughness or resistance to brittle fracture were developed over the cryogenic temperature range. These indices of resistance to brittle fracture

include notched/unnotched tensile ratios, Gc values, and critical crack length data.

Concurrently with this cryogenic work at Convair-Astronautics, the Convair-Fort Worth Division had been studying the materials problems associated with nuclear powered aircraft. These studies included thorough investigations of radiation damage in a wide variety of airborne materials at room and elevated temperatures which include structural materials hydraulic oils and other organic fluids, electronic components and systems, and many others. The nuclear reactor at the Convair-Fort Worth Division has proven to be an excellent experimental tool for this type of work.

With this background in cryogenics and nuclear radiation effects, it followed naturally that these two disciplines would be combined for a coordinated study of the materials problems involved in the RIFT program. Since it was immediately apparent that the problem of radiation damage at cryogenic temperatures would be of utmost and possibly controlling importance in the design of any nuclear powered upper stage vehicle using liquid hydrogen as a working fluid, these two Convair divisions collaborated in the preparation and execution of an experimental program to study this problem area.

The test program, currently in progress, entails smooth, notched, and welded joint tensile tests on a series of typical high strength sheet alloys after the samples have received an integrated neutron flux of 10^{17} nvt (This dose approximates that expected in the RIFT program). The samples will be irradiated while being held at both 70°F and -423°F, and then the tensile tests will be conducted at 70°F and -423°F respectively, without intervening warmup for those samples irradiated and tested at -423°F. These tests will allow the smooth tensile strengths, the notched/unnotched tensile ratios, and the weld joint tensile strengths to be calculated for these conditions of radiation and temperature and compared to the unirradiated data, which have already been obtained. These data, which have already been obtained by Convair at -423°F, support the program by serving as preliminary screening guides, as well as serving as the basis of comparison. Typical data are given in Table I.

The alloys proposed for test are 301 and 310 stainless steel cold-rolled to the extra full hard temper, 2014-T6 aluminum, and A110AT titanium. (The chemical compositions of these alloys are given in Table III). These alloys were chosen because they represent current and advanced materials selection for this type of space vehicle application. The 301 stainless steel is currently being used on the Atlas and Centaur programs as the primary structural material at -297°F (liquid oxygen) and -423°F (liquid hydrogen). It is characterized by high tensile strength, ease of weldability, good corrosion resistance, and adequate resistance to brittle fracture at -423°F. Type 310 is included as a backup to Type 301. This backup is needed because Type 301 exhibits moderate embrittlement at -423°F due to the presence of martensite in its microstructure. It is believed possible that this embrittlement may become more serious under radiation, because radiation is known to promote solid state phase transformations such as the austenite to martensite reaction which occurs in this alloy. Type 310 in the extra full hard temper has a slightly lower tensile

strength than Type 301, but exhibits a microstructure that is fully austenitic. This microstructure results in a very high order of resistance to brittle fracture at cryogenic temperatures.

The 2014-T6 aluminum alloy is included because it is used in stiffened structures such as Titan and Thor at -297°F (liquid oxygen), and is to be used in the Saturn S-IV stage at -423°F (liquid hydrogen). These vehicles are typical of the structures that represent minimum weight when designed as stiffened structures. The weld joint ductility of this alloy is marginal at best, but experience has shown that by proper joint design and welding wire selection, serviceable joints can be produced. Thus 2014-T6 is the highest strength weldable aluminum alloy, and for these reasons is included in this program. The weld joint data are of extreme importance in this case because the weld tends to be brittle at -423°F, and with the added embrittling effect of radiation, the weld joint may be completely unserviceable for this application. If these test data confirm this possibility, major revisions in the design philosophy of welded aluminum structures will be required since the lower strength 5000 series alloys (e.g., 5086, 5456) would have to be used, and this would mean major weight penalties.

The titanium alloy is selected as an example of advanced design philosophy. This alloy remains tough at -423°F, and exhibits unusually large increases in tensile and yield strengths between 70°F and -423°F. If design tolerances are based on the low temperature properties, which is completely reasonable for this application, the choice of this alloy may result in weight savings of 25-30 percent for certain upper stage vehicles. Thus, this alloy was selected on the basis of its potential for structural application in the near future.

Another problem of importance is that of induced radioactivity in the Rift structure. When the Rift vehicle is recovered the engine will be by far the most radioactive part of the structure. However, if it is decided to detach the engine from the airframe for ease of maintenance, etc., the level of induced radioactivity in the structure will determine how soon the airframe can be handled (or how much shielding will be required for safe handling). The level of induced radioactivity depends on the energy spectrum and exposure time of the incident neutron flux, and then on the decay time following the end of exposure. For very short times after exposure (less than 6 hours) all three alloys (i.e., stainless steel, aluminum, and titanium) are quite radioactive. However, after about 100 hours, the alloys exhibit decreasing radioactivities in the order of stainless steel, titanium, and aluminum, the amount of separation being about one order of magnitude between each alloy. (For relative calculations, see Figure 1 and Tables IV and V). Thus for recovery considerations immediately after re-entry, there is little choice between the alloys, and the radioactivity of the engine itself would be an overriding consideration anyway. However, for ease of maintenance after 100 hours, (assuming engine detachment), the order of preference would be aluminum, titanium, and stainless steel. The quantitative calculations as to how long a man could work on a stainless steel or other alloy tank 100 hours after

recovery before receiving a limiting dose, etc., must wait for final radiation exposure level and exposure time data.

It should be noted that alloying elements, sometimes in trace amounts, drastically change the induced radioactivity of certain alloys. Thus stainless steel derives most of its activity from its chromium, nickel and manganese contents. Likewise the difference in radioactivity level between pure titanium (75-A) and the 8 percent manganese alloy is two orders of magnitude after 100 hours (see Table V). Thus the possibility of minor changes in alloy content which would vastly improve the induced radioactivity level while not changing mechanical properties significantly would become a major materials development program in support of the Rift program.

Other aspects of impurity content will also require metallurgical study. The presence of impurities in trace amounts may be very important in certain alloys subjected to irradiation. For example, those elements that produce gases as a result of radioactive decay may embrittle alloys normally regarded as tough. For example, boron will yield helium, and magnesium will yield neon as a result of their respective decay schemes. Thus the presence of boron in stainless steel may severely embrittle it under radiation. Two heats of extra full hard 301 stainless steel were analyzed for boron, and both samples were found to contain 0.004 percent boron (40 ppm). Work by Blewitt and co-workers at the Oak Ridge National Laboratories has shown that boron levels between 20 and 50 ppm cause grain boundary embrittlement due to the boron to helium conversion under high levels of integrated neutron flux.(5). Thus the 301 and 310 grades may have to be modified to specify lower boron levels (6 ppm grades have been produced) to minimize this type of embrittlement under intensive radiation.

Other work suggests that titanium may become embrittled as a result of radiation damage in the same way that it is embrittled by oxygen, hydrogen, carbon, or nitrogen. Since these elements are believed to embrittle titanium by their interstitial position in the metallic lattice, it is postulated that neutron radiation which knocks titanium atoms into interstitial positions may also embrittle titanium alloys. This hypothesis will require experimental verification.

Another aspect of radiation is its tendency toward accelerating solid state phase transformations. In Type 301 stainless steel for example, it is believed that radiation would promote the austenite to martensite phase transformation. Since excessive martensite is known to embrittle this alloy at low temperature, it is recommended that fully stable alloys such as Type 310 be specified for this type of application.

Likewise, the age hardening reaction in 2014-T6 aluminum which accounts for the high strength of this alloy may be accelerated with resulting overaging and softening. Study of these solid state phase transformations will be part of the materials research program supporting the Rift program.

A final point of general importance is that of high temperature properties which

become important when re-entry and recovery of the Rift vehicle are considered. The re-entry envelope is actually controlled by the temperature to which the primary structure will retain useful strength. The 301 and 310 stainless steels are good to about 1000°F, A110AT titanium to 700°F, and aluminum to 250°F. Thus the advantages of the stainless steel and titanium alloys are apparent, and mean that insulation or special re-entry surfaces would be required for the aluminum and possibly the titanium alloys.

COLD WORKED 300 SERIES STAINLESS STEELS

In the cold rolled condition, this alloy class including Types 301 and 310, exhibits an outstanding combination of properties which suits it for structural application in missiles and space vehicles utilizing cryogenic propellants. These properties include good strength/density ratios, excellent toughness over the range of -423°F to +800°F, good weldability, good corrosion resistance and excellent formability.

Type 301 cold-rolled about 60 percent is the skin material used in the Atlas and Centaur vehicles. As such, it has been subjected to an extremely wide variety of mechanical and physical property tests including mechanical property tests over the temperature range of -423°F to 1000°F, weldability tests involving heliarc butt, seam, and spot welds, and resistance spot welds, stress corrosion tests, thermal conductivity tests, and many others. Similar, although less exhaustive, tests have been made on Type 310 stainless steel cold-rolled 75 percent. As a result of these tests the properties of these materials are accurately known for applications such as the Rift vehicle. At present, these alloys are being produced to a Convair specification which requires fractional standard AISI tolerances for thickness, camber, flatness, and surface appearance. These closer tolerances resulting from cold-rolling by the Sendzimir process, assure a more uniform product, which in turn improves the design accuracy in such vitally important areas as weight, and stress distribution. These advantages accrued to Convair-Astronautics only after long and continuous cooperative effort with the steel producers, of whom at least four major producers have qualified for the production of sheet to our requirements. Thus the current availability of these special materials resulting from this development program would be of direct and immediate benefit to new space vehicle programs such as Rift.

The 301 extra full hard exhibits a tensile strength which increases from about 220 ksi at +78°F to about 330 ksi at -423°F, while the yield strength increases from about 200 ksi to 285 ksi over the same temperature range. This immediately raises the possibility of using the low temperature properties as the basis of design allowables, when the structure is subjected to maximum loading only at low temperature. In the new space vehicles it is recommended that the low temperature properties be used wherever possible, to obtain an increase in yield strength, and consequent weight reduction. This procedure is now used in selected areas of the Centaur vehicle.

The increase in yield and tensile strength in this alloy is accompanied by an increase in elongation from about 5 percent at 78°F to about 20 percent at -320°F, and then by a decrease to between 6 and 14 percent at -423°F. The increase between +78°F and -320°F is due to a change in the nature of deformation between these temperatures. At +78°F, this material deforms by necking over a narrow range, so that the elongation measured over the standard 2 inch gauge length is relatively low, although strain at the necked area is much higher. At -320°F however, this material elongates uniformly over the entire gauge length, with a resulting higher elongation.

Between -320°F and -423°F, the occurrence of the austenite to martensite reaction causes the material to fracture in a less ductile manner (i.e., less plastic flow prior to fracture) with a resulting lower elongation.

The product of this reaction, martensite, behaves in a more brittle manner than does the austenite, and its presence in large amounts has a deleterious effect on the notched/unnotched tensile ratio and tensile fatigue properties of complex welded joints, and makes the use of this alloy marginal at -423°F. For example, a decrease in the notched/unnotched tensile ratio from 0.99 to 0.92 between -320°F and -423°F is accompanied by a decrease in cycles to failure in axial fatigue tests from 2003 cycles to 633 cycles (at the same stress level of 140,000 psi) between the same temperatures. Thus a moderate condition of embrittlement exists in this alloy at -423°F, and the severity of the service application (stress level, stress concentrations, etc.) will determine if this alloy can be used.

Since the formation of the more brittle martensite phase is known to be favored by low temperature and high tensile stress, and is believed to be favored by high intensity neutron fluxes, the final decision was against the use of 301 stainless steel cold-rolled 60 percent since it might possibly behave in an excessively brittle manner during the Rift flight profile.

For higher resistance to brittle fracture where better fatigue life for a given stress level is desired, a more stable steel (i.e., one in which the austenite to martensite reaction does not occur) would be specified. Such a steel is AISI Type 310 CRES, which has been tested in the 40, 60 and 75 percent cold rolled conditions.

In the 75 percent cold rolled condition this alloy sacrifices some strength at 78°F as compared to extra full hard Type 301 to obtain complete stability. However, the increased strength of 310 at lower temperatures exceeds the room temperature strength of Type 301. Thus where the steel is stressed only at low temperature, Type 310 imposes no weight penalty where room temperature properties are the basis of design allowables. This stability of type 310 is reflected by the higher fatigue life of this material in the welded joint at -423°F. After 2000 cycles (0-140,000 psi) at -423°F, only one small crack had appeared. Based on prior experience in fatigue tests where final failure occurs after 50 percent or more of the number of cycles at which the first crack initiates, it can be conservatively estimated that the fatigue life of this material will be at least 3000 cycles at -423°F; this compares with 633 cycles for the 301 CRES at -423°F.

Because of the optimum toughness of this alloy, as measured by both axial fatigue and notched/unnotched tensile tests, Type 310 stainless steel cold rolled 75 percent was selected as the primary structural alloy for the Rift vehicle.

TITANIUM ALLOYS

The titanium base alloys are of major interest for missile and space vehicle application because of their outstanding strength/density ratios, accompanied by good weldability, and excellent corrosion resistance. Convair-Astronautics has been in the forefront of titanium alloy use in missile application, and this work is best typified by the successful development and use of the 6Al-4V titanium alloy in the helium pressurization bottles which form part of the pneumatics system of the Atlas missile. These bottles contain helium gas under high pressure, and are cooled in liquid nitrogen (at -320°F) until just prior to takeoff in order to increase their gas storage capacity. Immediately after takeoff, these bottles are subjected to extreme vibrational loading due to their proximity to the rocket engines, while at low temperature. Thus, this application requires a high order of resistance to brittle fracture, which is possessed by this alloy. For the helium bottle application, the 6Al-4V-Ti alloy is solution quenched and aged to a tensile strength in the range of 155,000 to 165,000 psi.

Alloy A110AT was selected for study in this program because it is characterized by large increases in both tensile strength and yield strength and very small decreases in elongation with decreasing temperature. This large increase in yield strength is of prime importance in missile design, because many designs are based on yield strength rather than tensile strength, and large increases in yield strength at low temperature can be used to advantage in structures which are highly stressed only at low temperature.

However, in most cases where yield strength increases rapidly with decreasing temperature, the toughness of the alloy undergoes a transition from ductile to brittle behavior at relatively high temperatures, depending on chemistry, heat treatment, strain rate, type of test, etc. However, this titanium alloy displays an excellent notched/unnotched tensile ratio down to -423°F, and appears to be a promising alloy for cryogenic application in all respects. It should be noted, however, that this alloy loses strength rapidly at temperatures exceeding 600°F.

The welded joint of A110AT is as strong as the parent metal because this alloy does not respond to heat treatment. Thus material air cooled from the welding (molten) temperature has the same strength as the parent material. In tensile tests of heliarc butt welded joints, fracture occurred in the base metal rather than in the weld metal because the weld had been roll planished, thus increasing its strength slightly by cold work.

On a strength-weight basis, the A110AT titanium alloy (5Al-2.5Sn) is superior to the best steel and aluminum alloys at cryogenic temperatures; as shown in Table II, where the strength-weight characteristics of cold-rolled Types 301 and 310 stainless steel sheet, 2014-T6 aluminum alloy, and A110AT titanium alloy are shown at +78°F, -320°F, and -423°F.

Repeated loading tests of large welded joints (38" long coupon 4" in width with transverse heliarc butt joint made with no filler metal added, and in as-welded condition) were run on the 0.020 inch sheet material at +78, -320 and -423°F. The specimens were axially loaded to 90% of their typical yield strength at each temperature. More than 2000 cycles were obtained at room temperature (maximum stress of 100,000 psi) and at -320°F (stress level of 162,000 psi) without failure or indication of failure (cracking). 539 cycles were obtained at -423°F (stress level of 205,000 psi) without failure in the test section (specimen failed in end doubler due to the nature of the test equipment). These tests validate three important points. First, that 5Al-2.5Sn titanium alloy retains sufficient toughness for structural applications at -423°F. Secondly, that straight heliarc butt welds without post treatment or doublers are 100% efficient down to -423°F. And, third, that the very large increase in tensile and yield strengths (100% increase from +78 to -423°F) may be used to advantage in those structures which see maximum stress only while at low temperature.

Of the large number of titanium alloys tested, the 5Al-2.5Sn alloy is the only one being recommended at this time for structural use in liquid hydrogen (-423°F). It is possible that the annealed 6Al-4V-titanium alloy may possess good toughness at -423°F if the interstitial content were kept very low, lower than presently found in commercial heats. This point is being further investigated. The 5Al-2.5Sn titanium alloy is readily available in gauges 0.020 inches and thicker and an effort to produce 0.010 inch material by rolling rather than chemical milling is presently being made. Resistance spot or fusion welding of the 5Al-2.5Sn alloy to itself or to commercially pure titanium is considered excellent. Present production welding equipment used in the Atlas and Centaur programs is capable of resistance spot welding this alloy with no equipment changes required. Fusion welding may also be accomplished on present equipment with minor modifications, in particular, an increase in inert gas shielding. Corrosion resistance of the base metal and fusion welds is excellent. Also, the alloy is compatible with liquid hydrogen, and many storable propellants, such as pentaborane, hydrazine, UDMH and nitrogen tetroxide.

In conclusion, alloy A110AT is regarded as an excellent prospect for weight savings on future vehicles where optimization of design will be emphasized. For the Rift vehicle however, the cold-rolled 310 stainless steel was chosen in preference to A110AT titanium because of the wider background of knowledge immediately available with the stainless steel.

ALUMINUM ALLOYS

The aluminum alloys have been a favorite cryogenic structural material because of their good low temperature toughness, low density, moderately high strength, and good weldability. These generalities do not apply to all aluminum alloys, of course, and each general category must be studied separately for application in aerospace vehicles.

The 5000 series aluminum alloys which contain varying amounts of magnesium in solid solution, are noted for their weldability and low temperature toughness which is derived from their single phase face centered cubic structure. A high magnesium, aluminum base alloy was used for liquid oxygen tankage on the German V-2 rocket, and this type of alloy remains in use today on the Saturn first stage, which is fabricated from 5456 -H343. This alloy contains about 5 percent magnesium in solid solution, and is cold-rolled a small amount. Similar alloys used on earlier missiles such as the Jupiter and Jupiter-C were 5052 and 5086 which contain about 3 and 4 percent magnesium respectively. The higher magnesium contents increase strength levels, but tend to lower the low temperature toughness of these alloys, as well as introducing stress corrosion problems. By cold-rolling the softer alloys such as 5052, and 5086, equivalent strength levels to 5456 -H343 can be obtained with much better low temperature toughness, as measured by notched/unnotched tensile ratios. This avenue of alloy development is now being actively pursued in a number of laboratories with promising results.

The 2000 series aluminum alloys are the well-known age hardening alloys containing copper as their major alloying constituent. These alloys, notably 2014-T6 and 2024-T4, have much higher tensile and yield strengths than do the 5000 series, and for this reason are much more attractive for airborne tankage. However, since pressurized cryogenic fuel tanks require welded joints for pressure integrity, the weldability of these alloys becomes of major concern. Fusion welding of 2014-T6, for example, has always been regarded as marginal at best, because the weld joint exhibits poor ductility as measured by bend ductility tests. However, by designing around the weld joint problem with thickened weld joints (usually done by chem-milling), satisfactory structures have been produced. This type of design is typified by the Thor and Titan missiles, which utilize 2014-T6 as a primary structural material. The base metal properties of 2024-T4, 2014-T6, and 2219-T87 sheet are all acceptable at -423°F.

The 7000 series aluminum alloys contain zinc, copper, and magnesium, and in the heat treated condition, are the highest strength aluminum alloys commercially avaliable. Unfortunately, these high strength levels are accompanied by low resistance to brittle failure at cryogenic temperatures, and for this reason none of the 7000series alloys are recommended for liquid hydrogen service, and only 7079-T6 is acceptable for use at liquid oxygen temperature (-297°F). Again the weldability problem places severe limitations on the range of applicability of this alloy class at low temperature.

The 5000 and 2000 series aluminum alloys will undoubtedly remain as primary structural materials in the forthcoming series of upper stage space vehicles because in addition to the advantages enumerated, aluminum, by virtue of its low density, can be used in relatively thick sections, which is of major importance in lending stiffness to compression type structures. In most cases tank stiffness increases with the square of the wall thickness. Thus for various alloys of the same strength: density ratio, only magnesium and

beryllium would exceed the stiffness of an aluminum structure and neither of these metals and their alloys is an acceptable choice for low temperature structural application.

Alloy 2014-T6 was chosen for analysis in connection with the Rift program on the basis of its high strength/density ratio. This alloy also has a very short half life, but was finally rejected for use in favor of cold-rolled 310 CRES because of its poor high temperature properties, which become important during reentry, and because of its inherently unreliable weld joint toughness. A final point was that in order to make most efficient use of this alloy, a stiffened sheet stringer design is required, and this design was not favored for reasons outlined under the structural design portion of the Rift study.

The other effects of radiation on materials have been studied in great detail in both government and private laboratories, and Convair-Astronautics would propose to make use of this information and conform to recognized design practices. This includes the use of organic materials in high gamma fields and semiconductors and other electronic equipment in neutron fields. For example, certain hydraulic fluids are known to have maximum resistance to degradation under irradiation; Viton A is known to have relatively good resistance to degradation among the plastics; a new Teflon compound known as 100 X is known to have relatively good properties under high gamma doses; and many other such pieces of data are well known and reported. In the electronic field, similar engineering data are available, and would be applied to the design of the Rift vehicle. Detailed consideration of this problem area is given in the electronics portion of the Rift study. These massive compilations of data may be reviewed by reference to the bibliography (6,7,8). No new major problem areas are foreseen in these areas for the Rift vehicle.

BIBLIOGRAPHY

(1) Watson, J. F., and Christian, J. L., "Selection of Materials for Cryogenic Applications in Missiles and Aerospace Vehicles" Convair Astronautics Report MRG-132-1, Feb. 25, 1960.

(2) Christian, J. L., Chafey, J. E., and Girton, L. D., "Selection of Materials for Saturn (SII) Vehicle", Convair-Astronautics Report Nov. 16, 1960.

(3) Hurlich, A., "Booster Materials Document Dyna-Soar Program - Atlas and Centaur Materials and Their Selection Criteria (Confidential), Convair-Astronautics Report MRG-55, Jan. 7, 1960.

(4) Blewitt, T. H., Coltman, R. R., Jamison, R. H., and Redmond, J. K., "Radiation Hardening of Single Crystals", J. Nuclear Materials, to be published.

(5) Blewitt, T. H., unpublished data.

(6) "Reactor Handbook", Vol I, (Materials), edited by Tipton, C. R. Jr., Interscience Publishers, New York, N. Y., 1960.

(7) "The Effects of Radiation on Materials", edited by Harwood, J. J., Hausner, H. H., Morse, J. G., and Rauch, W. G., Reinhold Publishing Corp., New York, N. Y., 1958.

(8) Radiation Effects Information Center Reports, Battelle Memorial Institute, Columbus, Ohio:

a) The Effect of Nuclear Radiation on Elastomeric and Plastic Materials.
b) " " " " " " Structural Materials.
c) " " " " " " Lubricants and Hydraulic Fluids.
d) " " " " " " Silicone Elastomeric and Plastic Materials.
e) " " " " " " Semiconductor Materials.
f) " " " " " " Semiconductor Devices.
g) " " " " " " Electronic Components.
h) " " " " " " Protective Coatings.
i) Survey of Irradiation Facilities.
j) A Survey of Current Research and Developments in the Field of Dosimetry.

In addition, the following condensed technical memoranda have been received:

a) The Effect of Nuclear Radiation on Fluorinated Polymers in Different Environments.
b) " " " " " " Metallo-organic Compounds and a Polyethylene.
c) " " " " " " Transistors.
d) " " " " " " Semiconductor Diodes.
e) " " " " " " Electronic Transformers and Transformer Materials.
f) " " " " " " Seals, Gaskets, and Sealants.
g) " " " " " " Glass.
h) " " " " " " Hydrocarbon Fuels.
i) " " " " " " Magnetic Materials.
j) " " " " " " Organic Heat Transfer Materials.
k) " " " " " " Electrical Insulating Materials.
l) " " " " " " Hoses and Couplings.
m) " " " " " " Refrigerants.
n) " " " " " " Fluoropolymers.
o) " " " " " " The Performance of a Hydraulic Flight-Control System.
p) " " " " " " Resistors and Resistor Materials.

TABLE I

Low Temperature Mechanical Properties of High Strength Aerospace Vehicle Sheet Alloys

TEST TEMP °F	F_{ty} ksi	F_{tu} ksi	el %	NOTCHED T. S., ksi (K_t=6.3)	NOTCHED/ UNNOTCHED TENSILE RATIO	HELIARC BUTT WELD T.S., ksi	JOINT EFF. %	GAUGE IN.
301 Stainless Steel, 60 Percent Cold Rolled								
78	205	224	5	241	1.08	148[a]	66	.032
-320	249	316	20	301	.95	287	91	.032
-423	290	322	15	303	.92	215	67	.032
310 Stainless Steel, 75 Percent Cold Rolled								
78	160	179	3	197	1.10	88[a]	49	.020
-320	215	242	13	269	1.11	165	66	.020
-423	254	281	14	312	1.11	203	70	.020
A110 AT Titanium								
78	113	118	19	153	1.30	121[a]	100	.040
-320	184	196	15	226	1.15	192	98	.040
-423	230	246	15	239	.97	233	94	.040
2014-T6 Aluminum								
78	65.7	73.1	11	74.5	1.02	53.1[b]	73	.063
-320	74.4	87.1	14	85.5	.98	61.9	71	.063
-423	86.2	104	17	97.8	.94	75.6	73	.063

a Heliarc Butt Weld; roll planished; no doubler reinforcement.

b Filler Metal (2319) weld, tested with bead in place.

All data longitudinal

TABLE II

Strength/Density Ratios and Notched/Unnotched Tensile Ratios for High Strength Sheet Alloys at Cryogenic Temperatures*

ALLOY	TEST TEMP °F	F_{ty} psi/density lb/in.^{3} in.	F_{tu} psi/density lb./in.^{3} in.	NOTCHED/ UNNOTCHED TENSILE RATIO (K_t=6.3)	GAUGE in.	DENSITY lb/in.^{3}
301 CRES 60 percent Cold-Rolled	+78	$.64 \times 10^6$	$.76 \times 10^6$	1.08	.032	.29
	-100	$.73 \times 10^6$	$.83 \times 10^6$	1.04		
	-320	$.86 \times 10^6$	1.10×10^6	.95		
	-423	1.00×10^6	1.10×10^6	.94		
310 CRES 75 percent Cold-Rolled	+78	$.55 \times 10^6$	$.62 \times 10^6$	1.10	.020	.29
	-100	—	—	—		
	-320	$.74 \times 10^6$	$.84 \times 10^6$	1.11		
	-423	$.88 \times 10^6$	$.97 \times 10^6$	1.11		
2014-T6 Aluminum	78	$.65 \times 10^6$	$.73 \times 10^6$	1.02	.063	.101
	-320	$.74 \times 10^6$	$.87 \times 10^6$	.98		
	-423	$.86 \times 10^6$	1.04×10^6	.94		
A110 AT titanium	+78	$.70 \times 10^6$	$.74 \times 10^6$	1.34	.040	.161
	-100	$.84 \times 10^6$	$.88 \times 10^6$	1.22		
	-320	1.14×10^6	1.22×10^6	1.15		
	-423	1.43×10^6	1.52×10^6			

* data based on longitudinal properties

TABLE III

Chemical Compositions of Materials

	301 STAINLESS STEEL	310 STAINLESS STEEL	2014-T6 ALUMINUM	A110 AT TITANIUM
Chromium	17.00 - 19.00	24.00 - 26.00	.10	
Nickel	6.50 - 8.00	19.00 - 22.00		
Carbon	.10 Max.	.25 Max.		.15 Max.
Manganese	2.00 Max.	2.00 Max.	.40 - 1.2	.30 Max.
Silicon	1.00 Max.	1.50 Max.	.50 - 1.2	
Nitrogen	.06 Max.			.07 Max.
Phosphorus	.04 Max.			
Sulfur	.03 Max.			
Copper	.5 Max.			
Molybdenum	.50 Max.			
Iron	Balance	Balance	1.0	.50 Max.
Copper			3.9 - 5.0	
Magnesium			.2 - .8	
Zinc			.25	
Titanium			.15	Balance
Aluminum			Balance	4.00 - 6.00
Tin				2.00 - 3.00
Hydrogen				.003 - .020
Oxygen				.20 Max

TABLE IV

Chemical Compositions Used to Calculate Induced Radioactivity of Alloys

Shown in Figure 1

Alloy	Fe	Mn	Si	Ni	Cr	S	C	P	Mo	Cu
310 Steel*	48.2	2	1.5	22	26	0.03	0.25	0.04	-	-
309 Steel	57.9	2.42	0.3	14.7	24.6	0.01	0.21	0.03	0.10	
301 Steel	72.9	0.75	1.0	7.0	17	0.03	0.15	0.04	0.50	0.50
416 Steel	80.1	0.54	0.35	1.68	17	0.02	0.22	0.03	0.10	
	Fe	Mn	Si	Ni	Cr	Cu	Zn	Al	Mg	Ti
2014 Al*	1.0	1.2	1.2	-	0.1	5.0	0.25	89.3	0.8	0.15
2024 Al	0.71	0.53	0.21	0.02	0.13	3.88	0.11	93.0	1.45	
	Mn	Cr	Ti	Al	C	Sn	Fe			
A110AT Ti	0.2	-	91.6	5.7	-	2.4	0.09			
RS-140 Ti	0.12	2.22	91.0	4.67	0.09	-	1.87			

(data from Convair-Fort Worth)

* indicates nominal composition

TABLE V

THE AMOUNT OF RESIDUAL GAMMA RADIATION EMITTED BY METAL SPECIMENS AFTER EXPOSURE TO 4×10^{15} FAST NVT*

Metal	Decay Time, hours	Amount of Residual Radiation 1 Foot in Air Away From a 1 x 1 -Foot Sheet (a), ergs/hr-g(C)
Cr-Ni-Co alloy	1000	30,000
2014 aluminum	100	5.6×10^{-2}
2024 aluminum	100	4.7×10^{-2}
6061 clad aluminum	100	3.8×10^{-2}
7075 aluminum	100	2.53×10^{-1}
AZ31A magnesium	100	7.2×10^{-2}
AZ91 magnesium	100	4.2×10^{-2}
Inconel	100	5.31×10^{-1}
Monel	100	3.23×10^{-1}
SAE 4130 steel	100	8.13×10^{-1}
SAE 4340 steel	100	8.12×10^{-1}
301 stainless steel	100	1.018
321 stainless steel	100	1.045
347 stainless steel	100	1.551
Titanium (RS-70)	1	3.0×10^{-2}
Ti-8Mn (RC-130A)	10	200
Ti-175A	0.5	4.9×10^{-1}

(a) Safe laboratory level is 0.75 ergs/hr-g(C)
* Data from: Moller, M.P., Aviation Age, 21 (1) 20 (1954).

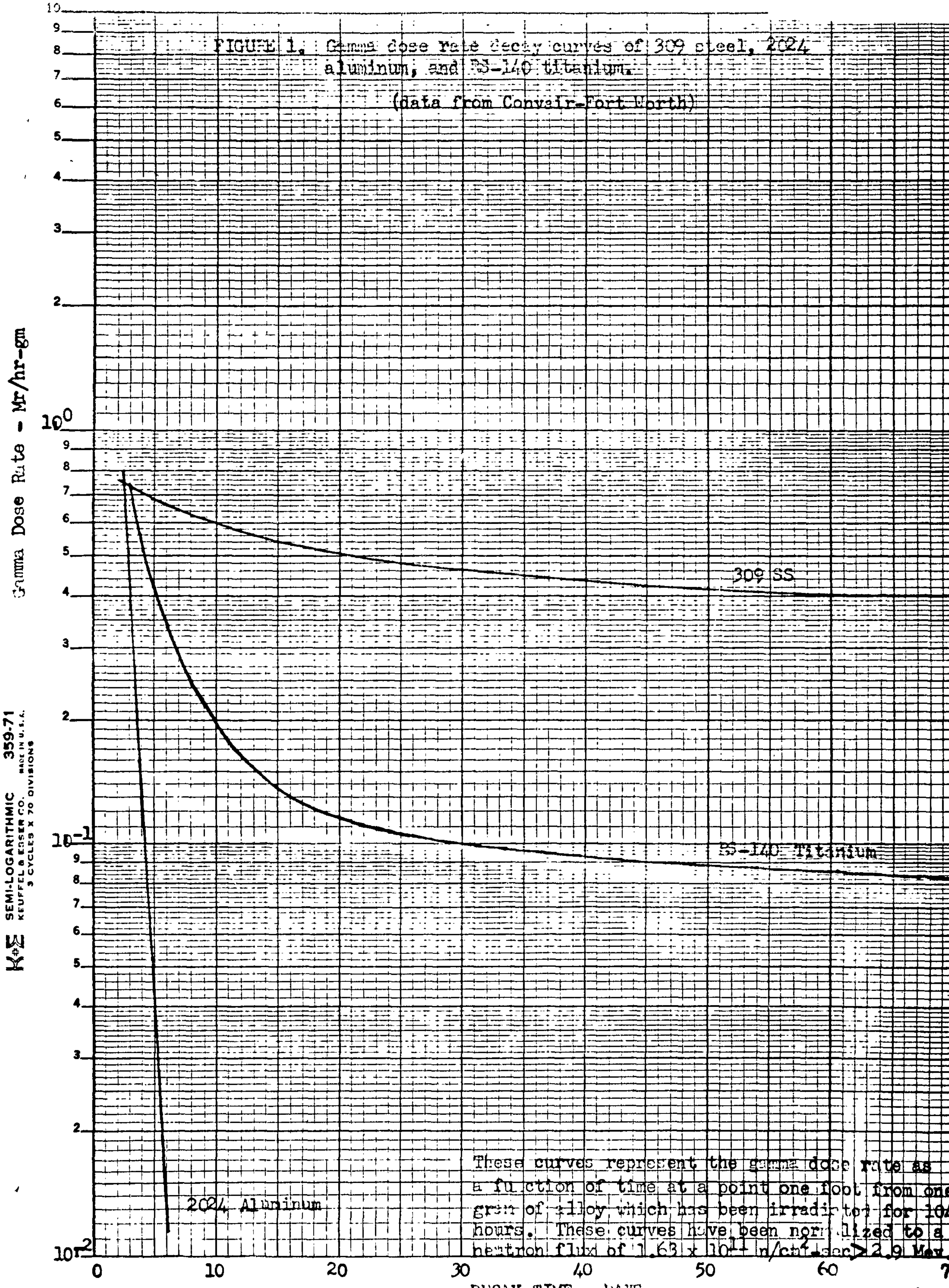

FIGURE 1. Gamma dose rate decay curves of 309 steel, 2024 aluminum, and RS-140 titanium.

(data from Convair-Fort Worth)

These curves represent the gamma dose rate as a function of time at a point one foot from one gram of alloy which has been irradiated for 104 hours. These curves have been normalized to a neutron flux of 1.63 x 10^{11} n/cm^2-sec > 2.9 Mev.

9 May 1961

SUBJECT: The Cryogenic Tensile Properties of Cold Worked 20% and 25% Nickel Steels.

ABSTRACT: The tensile properties of 20% Ni and 25% Ni alloy steels in the 50% cold worked condition were determined at room and cryogenic temperatures. Properties were determined in both the longitudinal and transverse directions of sheet stock .020" thick. Notched-unnotched ratios were determined at all temperatures. Excellent toughness, as defined by the notched-unnotched ratio criterion, was observed even at -423°F.

Prepared by E. B. Mikus
E. B. Mikus

Approved by A. Hurlich
A. Hurlich
Research Group Engineer
Materials Research Group

AH:EBM:bts

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FROM: Materials Research Group, 592-1

SUBJECT: The Cryogenic Tensile Properties of Cold Worked 20% and 25% Nickel Steel

INTRODUCTION

Within recent months a family of new steel alloys containing 20% and 25% nickel have been developed by the International Nickel Company. Because these alloys have a favorable chemistry and exhibit a suitable strengthening mechanism, they may be excellent alloys for use at cryogenic temperatures.

On this basis an evaluation program of these alloys was initiated to determine the cryogenic properties of these alloys.

MATERIALS

The materials investigated in this program were supplied at no cost by the International Nickel Company and had the following chemistry:

	C	Mn	P	S	Si	Ni	Ti	Al	Cb
Heat 23222 Stock No. 04113	0.007	0.105	0.007	0.002	0.15	20.04	1.27	0.22	0.52
Heat 23223 Stock No. 04113	0.006	0.12	0.008	0.002	0.17	25.33	1.37	0.20	0.54

The alloys were tested in the 50% cold worked sheet condition and were 0.020" thick.

These alloys are hardened by two mechanisms:

1. Precipitation reaction at 800-950°F in which a $Fe_x\ Ti_y$ type precipitate is formed.

2. Martensitic transformation produced by cold work. The martensite in these alloys does not exhibit tetragonolity because of the low carbon content.

The nickel content of these alloys has a profound effect on the response to heat treatment and cold work.

After a 1500°F anneal, for example, the 25% Ni alloy has an Ms temperature of -150°F compared to +200°F for the 20% Ni alloy. The work hardening

response for the two alloys differ appreciably, as well. The 25% Ni alloy strain hardens at a slower rate than the 20% Ni alloy. This characteristic is important when forming operations are employed during fabrication.

RESULTS

The tensile properties of 20% Ni alloy and 25% Ni alloy obtained at room temperature, -100°F, -320°F and -423°F, are presented in Tables I and II. Both longitudinal and transverse directions were employed in smooth and notched specimen configurations.

A summary plot of these data is shown in Figure 1. The results show that both alloys respond to low temperature testing in a similar manner, i.e., the tensile and yield increases as the temperature decreases. The rate at which the yield increases with decreasing temperature appears to be greater than the rate at which the tensile strength increases. This tendency would indicate that brittle failure may be predominate at very low temperatures. However, using notched/unnotched ratio as a criterion, Figure 2, the toughness of these alloys remains high even at -423°F.

The excellent strength and toughness of these alloys make them candidates for cryogenic missile applications. However, before these alloys can be employed in competition with 301 s.s. the room temperature tensile properties needs to be increased. This may be accomplished by one of several heat treatments to which these alloys respond, in conjunction with cold work. If, in this higher strength condition, the alloys remain tough at low temperatures, a further question to be investigated is the weldability of these materials.

CONCLUSIONS

From the data obtained on these materials it appears that the 20% Ni and 25% Ni alloys in the 50% cold worked condition possess excellent notch toughness and tensile strength at temperatures down to -423°F.

In the 50% c. w. condition the alloys do not possess sufficient room temperature tensile properties to compete favorably with 301 ss X FH in a missile skin application.

The response of these alloys to precipitation hardening may offer a solution to the problem of low room temperature tensile properties. However, this solution is only sound if the cryogenic properties of the heat treated alloy have not deteriorated.

TABLE I

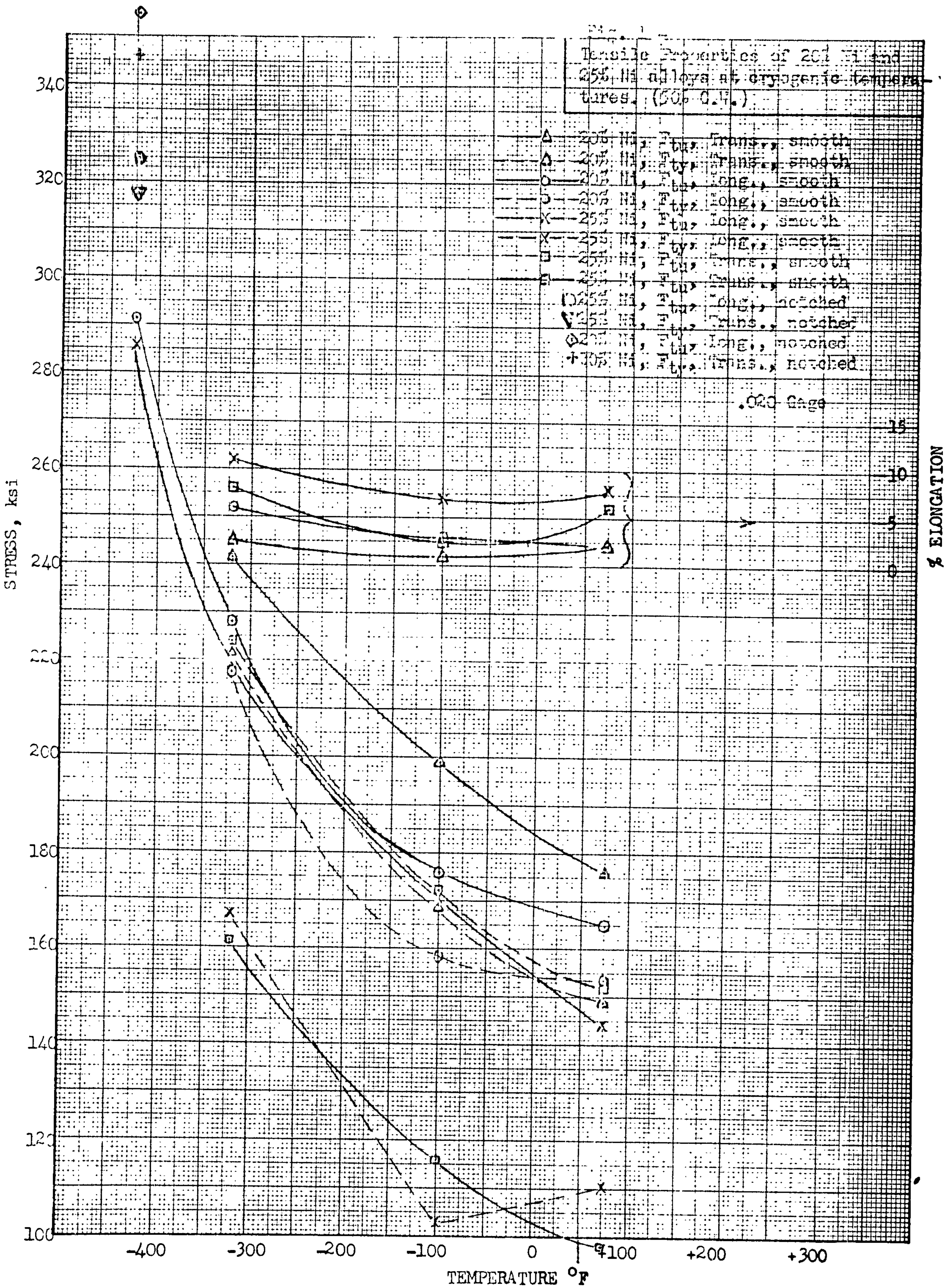
Mechanical Properties of 50% Cold Rolled 20% Ni Steel
0.020" Thick, INCO, Ht. #23222

Test Temp	Direction	F_{ty} ksi	F_{tu} ksi	e %	Notched T.S. ksi K_t=6.3	Notched/ Unnotched Tensile Ratio
78°F	Long.	151	165	2	181	
		153	165	2	207	
		157	166	2	209	
	Avg.	154	165	2	199	1.21
78°F	Trans.	151	176	2	183	
		142	175	2	191	
		154	177	2	189	
	Avg.	149	176	2	188	1.07
-100°F	Long.	154	177	-	202	
		147	187	3	205	
		174	184	3	203	
	Avg.	158	183	3	203	1.11
-100°F	Trans.	176		.5	225	
		-			213	
		162	199	.5	225	
	Avg.	169	199	.5	221	1.11
-320°F	Long.	219	229	5.5	244	
		217	227	5.5	247	
		-	223	-	267	
	Avg.	218	226	5.5	253	1.12
-320°F	Trans.	218	244	3.5	270	
		219	238	2.0	266	
		229	243	3.0	-	
	Avg.	222	241	3	268	1.11
-423°F	Long.	-	291	6	355	1.22
-423°F	Trans.	-	-	-	346	-

TABLE II

Mechanical Properties of 50% Cold Rolled 25% Ni Steel
0.020" Thick, INCO, Ht. #232223

Test Temp	Direction	F_{ty} ksi	F_{tu} ksi	e %	Notched T.S. ksi Kt=6.3	Notched/ Unnotched Tensile Ratio
78°F	Long.	109	143	7.5	180	
		112	144	7.5	170	
		111	145	7.5	165	
	Avg.	111	144	7.5	172	1.19
78°F	Trans.	97	150	6	168	
		98	152	6	165	
		100	154	6	-	
	Avg.	98	152	6	167	1.10
-100°F	Long.	-	172	8	197	
		102	170	7	196	
		104	170	5.5	188	
	Avg.	103	171	7.0	194	1.13
-100°F	Trans.	102	176	3.5	202	
		87	167	2.0	192	
		130	173	-	191	
	Avg.	106	172	3	195	1.13
-320°F	Long.	167	216	12	248	
		171	220	10.5	244	
		164	221	11	248	
	Avg.	167	219	11	247	1.13
-320°F	Trans.	156	222	8	246	
		164	226	8	240	
		163	225	=	248	
	Avg.	161	224	8	245	1.09
-423°F	Long.	-	286	-	325	1.14
-423°F	Trans.	-	-	-	317	



Tensile Properties of 20% Ni and 25% Ni alloys at cryogenic temperatures. (50% C.W.)
20% Ni, Ftu, Trans., smooth
20% Ni, Fty, Trans., smooth
20% Ni, Ftu, Long., smooth
20% Ni, Fty, Long., smooth
25% Ni, Ftu, Long., smooth
25% Ni, Fty, Long., smooth
25% Ni, Ftu, Trans., smooth
25% Ni, Ftu, Trans., smooth
25% Ni, Ftu, Long., notched
25% Ni, Ftu, Trans., notched
20% Ni, Ftu, Long., notched
20% Ni, Ftu, Trans., notched
.020 Gage
STRESS, ksi
% ELONGATION
TEMPERATURE °F
340
320
300
280
260
240
220
200
180
160
140
120
100
-400
-300
-200
-100
0
+100
+200
+300
15
10
5
0

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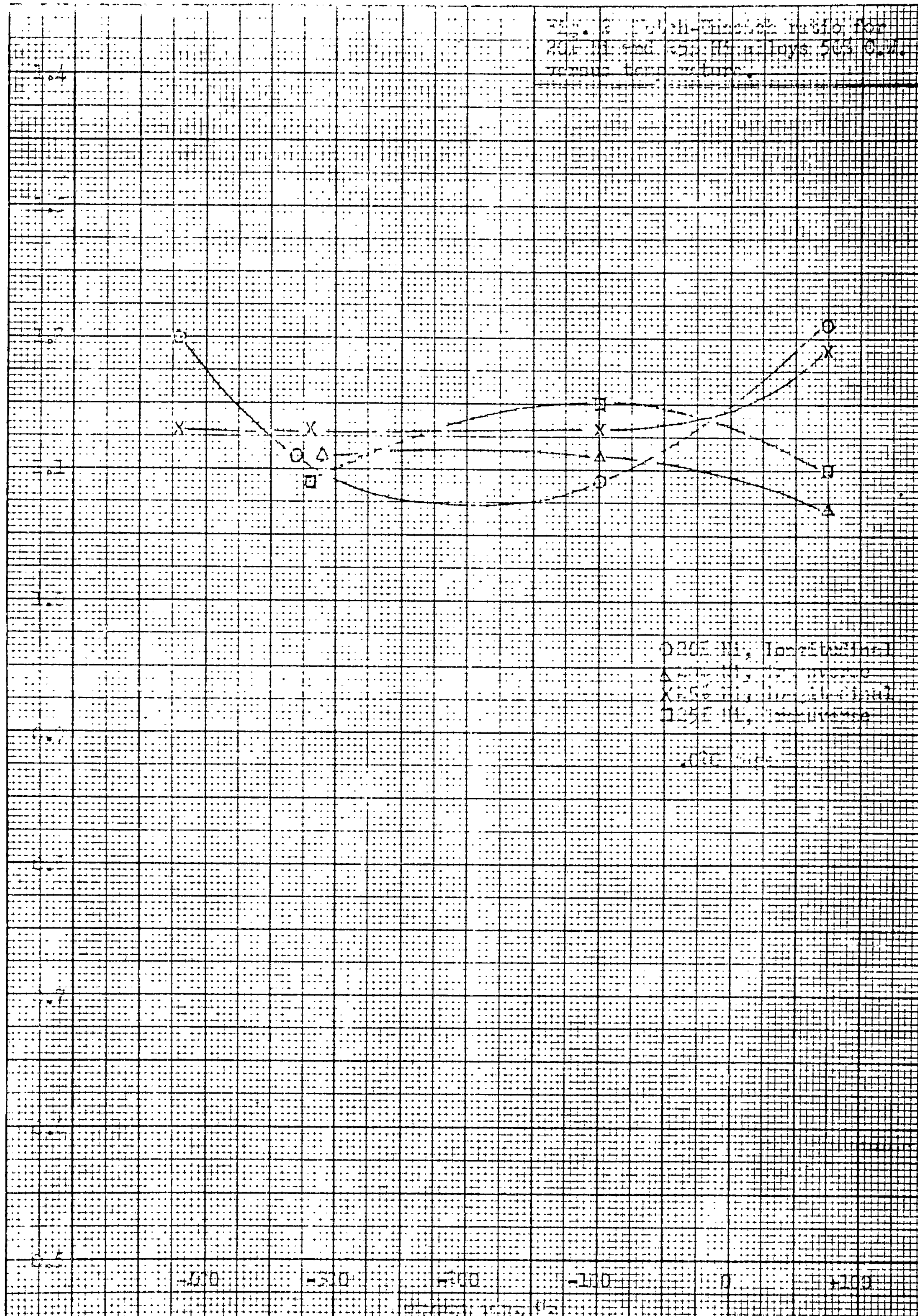

SUBJECT: Influence of Creep Damage on the Toughness of Ti-5Al-2.5Sn and 301 Stainless Steel XFH at -423°F.

ABSTRACT: The notched/unnotched tensile strength ratios of Ti-5Al-2.5Sn and 301 S.S. XFH were determined at -423°F before and after creep testing at 600°F. Creep damage was achieved by stressing both alloys at 600°F for 24 hours. Under these conditions a stress of 69,000 psi produced 0.014 in/in of creep strain for Ti-5Al-2.5Sn, and a stress of 168,000 psi produced 0.0027 in/in of creep strain for the 301 S.S. XFH. The creep damage produced in the Ti alloy reduced the low temperature notched/unnotched tensile strength ratio from 0.62 to 0.56 at -423°F. For 301 S.S. XFH the creep damage sustained at 600°F caused a reduction in notched/unnotched ratio from 0.96 to 0.86 at -423°F. These reductions in fracture toughness illustrate a trend which required verification by additional testing.

The ramifications of these observations are discussed in relation to applications such as a recoverable booster system, nuclear reactor rocket engine and reusable winged space planes.

Prepared by E. B. Mikus
E. B. Mikus

Prepared by R. L. Jones
R. L. Jones

Approved by A. Hurlich
A. Hurlich
Research Group Engineer
Materials Research Group

AH:EBM:RLJ:bts

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FROM: Materials Research Group, 592-1

SUBJECT: Influence of Creep Damage on the Toughness of Ti-5Al-2.5Sn and 301 Stainless Steel XFH at -423°F.

INTRODUCTION

In many of the structural alloy applications encountered in current space programs the material has been subjected to conditions of low temperatures and high stress. Under these conditions a most vital characteristic of a structural material is its fracture toughness or resistance to crack propagation at cryogenic temperatures.

There are two general classes of variables that affect the fracture toughness of a material. One is associated with the metallurgical characteristics of the alloy and includes such factors as chemical composition, crystalline structure, microstructure, impurities, heat treatment, etc. The second class includes factors which are superimposed on the alloy by virtue of the service conditions. These include: temperature, strain rate, stress concentration factors, complexities of stress distribution, etc.

The influence of these various factors upon the fracture characteristics of structural alloys is reasonably well known on at least a qualitative basis. However, the degree to which the fracture toughness of metals is affected by these variables applied in sequence or in combination is more difficult to determine.

It is the purpose of this report to relate the results of work aimed at determining the influence of a combination of factors, heretofore not studied, on the fracture toughness of two promising high strength structural alloys. This work was carried out under REA 111-9222.

The objective of this study is to explore the influence of prior creep at elevated temperatures upon the subseqent fracture toughness at cryogenic temperatures. Creep is defined as a time dependent deformation of a material under stress at elevated temperatures. As a result of creep at elevated temperature the subsequent mechanical properties of an alloy may be altered significantly. Minute lattice defects are generated during the creep exposure which leave permanent damage in the crystalline structure. On the basis of physical metallurgical principles these defects can affect the fracture toughness of an alloy at cryogenic temperatures to a significant degree.

The consequences of lowered fracture toughness by exposure to creep at elevated temperatures are of major significance to space vehicles that are designed to be re-useable and that utilize cryogenic propellants. A typical example of such a vehicle is the concept of a "recoverable booster". In this concept

the boost stage of a space ship complex is recovered aerodynamically after burnout. In the course of each flight the tank material encounters cryogenic temperatures during launch phase through use of liquid oxygen and possibly liquid hydrogen propellants and then aerodynamic heating during re-entry. The high temperature exposure during re-entry results in creep extension in the tank and wing sections of the booster vehicle. On each subsequent flight the tank material is subjected to additional cycles of cryogenic temperature exposure followed by creep extension during re-entry. If creep damage is encountered during re-entry the fracture toughness of the tank skin material at cryogenic temperatures might be reduced to a dangerously low level and could result in greatly reduced reliability during re-use of the booster.

Other examples of applications where creep damage may be a significant factor in design through this mechanism include: Space Plane, Dyna-soar, nuclear rocket boosters, and other re-usable vehicles.

MATERIALS

Two of the more promising high strength alloys were used in this investigation: Cold rolled Type 301 stainless steel sheet (Spec. GD/A 0-71004) and annealed 5Al-2.5Sn titanium alloy sheet. The chemical analyses of these alloys are given in Table I. The chemistry of the 301 S.S. conforms to the specification established for missile tank construction. However, the oxygen content of the titanium alloy exceeds the level established in Specification GD/A 0-71010, and can be expected to deleteriously affect the fracture toughness of the alloy at extreme sub-zero temperatures. The referenced specification limits the oxygen content to 0.12% and the 5Al-2.5Sn-Ti sheet alloy studied in this investigation had an oxygen content of 0.167%. This material was a commercial grade of the alloy and had not been procured to Specification GD/A 0-71010.

TEST PROCEDURES

Creep damage was accomplished by creep testing specimens having the configuration shown in Figure 1. The creep test procedure consists of placing the specimen without load into the creep furnace held at the required test temperature. Temperature equilibrium over the gage length of the specimen is achieved from ½ to 1 hour and is monitored by 3 thermocouples placed at the top, middle, and bottom of the reduced section of the specimen. After temperature equilibrium is achieved the load is applied and the creep strain is followed by a linear differential transformer having a span of .040 inch and an accuracy of ± 0.0001 in/in.

After creep testing the specimens were remachined into standard tensile coupons of smooth[1] or notched[2] configurations and tested at room temperature and $-423^{\circ}F$ using a 0.001 in/in/min strain rate to yield and 0.15 in/min head speed to fracture.

1. EMG-D-1
2. MRG-D-10 Notch A, $K_t=6.3$

RESULTS AND DISCUSSION

In order to establish some degree of creep damage whose influence on low temperature toughness could be evaluated, specimens of Ti-5Al-2.5Sn and 301 S.S. XFH were subjected to stresses at 600°F for 24 hours duration. The stress employed for the titanium alloy was 69,000 psi which was sufficient to cause a total creep strain of about 0.0138 in/in in 24 hours at 600°F. The creep curve determined on this alloy under the related conditions is shown in Figure 2. The 301 S.S. XFH alloy was stressed at 168,000 psi for 24 hours at 600°F. This exposure produced a total creep strain of 0.0027 in/in. The creep curve for this alloy is also shown in Figure 2. These creep deformation curves were established on the average value based on three separate tests for each alloy.

After creep exposure the samples were remachined so that they would fit the liquid hydrogen cryostat. Half of the samples exposed to creep damage at elevated temperatures were machined into notched tensile specimens (Drawing No. MRG-D-10) having a stress-concentration factor, K_t, of 6.3.

The results of the tensile tests performed on these specimens are presented in Table II for comparison.

Ti-5Al-2.5Sn

The titanium alloy did not exhibit any decrease in tensile properties at room temperature as a result of creep testing. At -423°F, however, the notched-unnotched ratio decreased from 0.62 to 0.56 as a result of creep exposure. The other properties such as smooth tensile, yield, elongation and elastic modulus seem to be unaffected by the prior creep exposure. The relatively low notched/unnotched ratio at -423°F of this alloy in the as-received condition is undoubtedly due to the high oxygen content of this alloy as discussed in conjunction with Table I. Further verification of this premise is obtained by observing the high yield strength of this particular alloy, 128.2 ksi, approximately 18,000 psi above its normally guaranteed level. This heat of the Ti-5Al-2.5Sn alloy would not be recommended for use at liquid hydrogen temperature because of its notch sensitivity in the as-received condition. While creep damage did lower its notched/unnotched strength-ratio from 0.62 to 0.56, similar testing must be performed on initially acceptable material having a notched/unnotched tensile ratio in the as-received condition in the range of 0.9 - 1.0 at -423°F before it is possible to evaluate the quantitative effect of prior creep damage on the fracture toughness of this alloy at cryogenic temperatures.

301 Stainless Steel

In the case of 301 S.S. XFH the tensile properties at room temperature were altered slightly by prior creep testing. The yield and ultimate tensile strengths increased while the elongation decreased. At -423°F the yield and

ultimate strengths did not change but the elongation decreased to 0.5% and the notched/unnotched ratio decreased to 0.86 from its original level of 0.96 as a result of prior creep exposure.

Both alloys showed evidence of creep damage resulting from prolonged stressing at a temperature of 600°F.

The critical amount of creep strain necessary to produce a deleterious effect on toughness is not known at this time. However, the creep strain employed in these initial tests represents a reasonable amount that might be encountered in structures. The more quantitative aspects of the relationship between creep damage and low temperature brittle fracture resistance must await further testing. In this study it has been demonstrated that a problem area may exist in reusable cryogenic tanks subject to creep during portions of its useful life.

CONCLUSIONS

Microstructural damage produced by modest creep exposure had a deleterious effect upon the subsequent toughness characteristics of 301 S.S. XFH and Ti-5Al-2.5Sn at -423°F.

The notched/unnotched strength ratio of 301 S.S. was reduced from 0.96 in the as-received condition to 0.86 at -423°F by 0.0027 in/in of prior creep strain at 600°F.

The notched/unnotched ratio of Ti-5Al-2.5Sn was reduced from an original value of 0.62 to 0.56 at -423°F by 0.014 in/in of prior creep strain at 600°F.

TABLE I

CHEMICAL ANALYSIS OF 301 S.S. AND Ti-5Al-2.5Sn ALLOYS

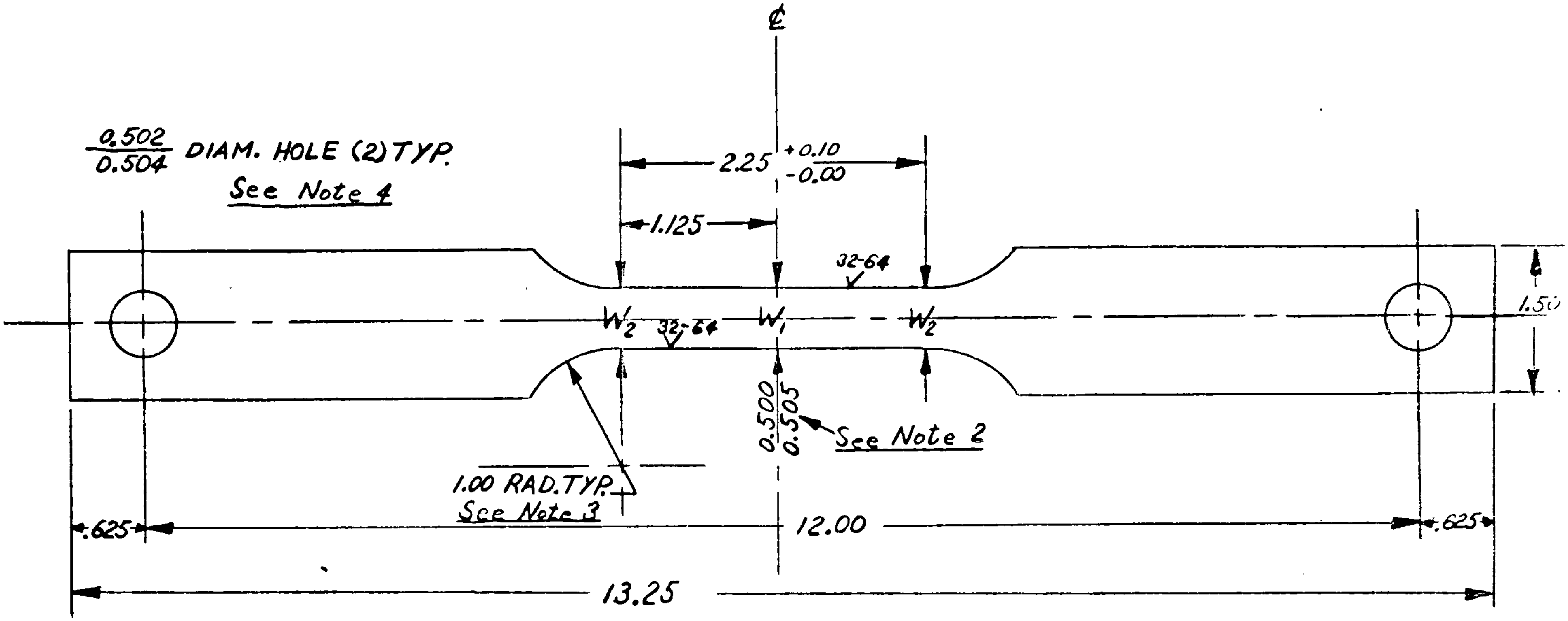
	Weight Percent											
	C	Cr	Ni	Mn	Si	Ti	Sn	Al	O	N	H	Fe
301 S.S.	0.07	17.58	7.14	1.12	0.71	-	-	-	-	-	-	Bal.
Ti-5Al-2.5Sn	0.038	-	-	.05	0.167	Bal.	2.53	5.14	0.167	.023	.0084	0.18

TABLE II

EFFECT OF PRIOR CREEP ON THE TENSILE PROPERTIES AT 75°F AND -423°F OF Ti-5Al-2.5Sn AND 301 S.S. XFH ALLOYS

Alloy and Condition	F_{ty} ksi	F_{tu} ksi	e %	Modulus of Elasticity x 10^6 psi	Notched Tensile ksi	Notched/ Unnotched Ratio	Test Temp °F
Ti-5Al-2.5Sn							
As Received	128.2[1]	129.7	21.7	16.7			Room
Creep Tested[2]	128.3	133.6	21.7	17.7			Room
As Received	238.2	261.9	4.5	16.1	139.0		
	241.0	261.9	4.0	18.4	183.8		
Avg.	239.6	261.9	4.3	17.3	161.4	0.62	-423
Creep Tested	238.5	245.8	-	17.7	167.9		
	242.3	260.1	4.0	18.3	117.7		
Avg.	240.4	252.9	4.0	18.0	142.8	0.56	-423
301 S.S. - XFH							
As Received	205.5	221.9	4.8	25.1			Room
Creep Tested[3]	222.5	247.8	2.0	26.1			Room
As Received	289.6	316.6	-	22.2	290.0		
	265.0	310.2	3.5	24.1	308.8		
Avg.	277.3	313.4	3.5	23.2	299.4	0.96	-423
Creep Tested	279.6	320.1	0.5	23.7	279.4		
	273.0	321.3	-	21.3	275.9		
Avg.	276.3	320.7	0.5	22.5	277.2	0.86	-423

1 Values shown for all non-creep conditions represent average of 3 samples. See MRG-247.
2 Creep tested 24 hours, 69,000 psi @ 600°F, average of 3 samples.
3 Creep tested 24 hours, 168,000 psi @ 600°F, average of 3 samples.



NOTES:

1. Holes on centerline of test section within ±0.005.
2. Gradual taper from W_2 to W_1 of 0.005 $^{+0.000}_{-0.002}$.
3. No undercut at intersection of radii and test section.

Figure 1 - Creep Specimen

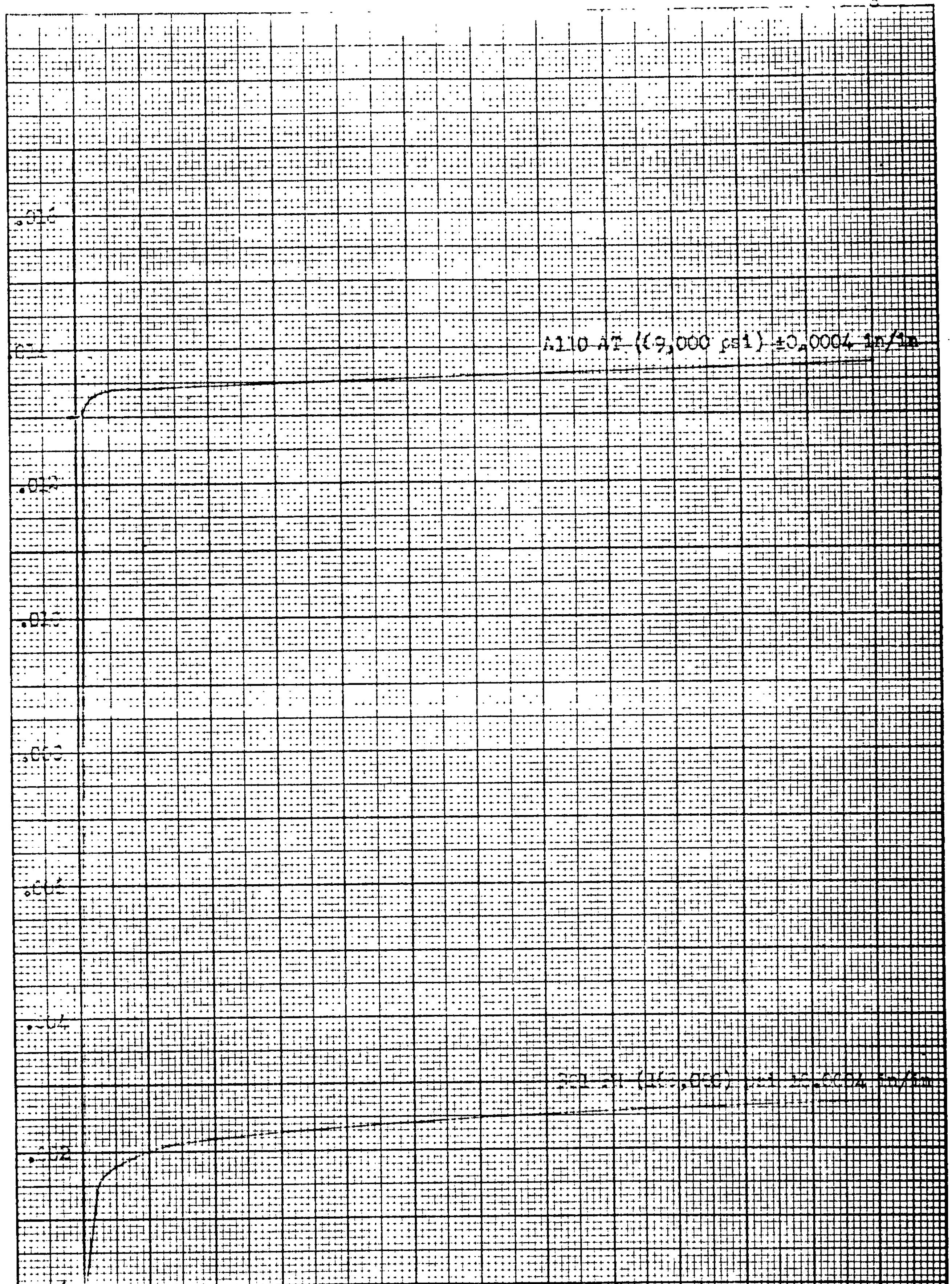


Figure 2 - Creep Curves for Ti-5Al-2.5Sn and 301 Stainless Steel YFH at 600°F

CONVAIR ASTRONAUTICS

REPORT MRG 266
PAGE 1
20 October 1961

SUBJECT: Determination of the Effect of Oxygen Content on the Mechanical Properties of Titanium - 5 Al-2.5 Sn Alloy At Room and Cryogenic Temperatures.

ABSTRACT: Tensile (F_{ty}, F_{tu} and elongation) properties, notched tensile strengths and notched/unnotched tensile ratios were determined on five heats of Ti-5Al-2.5 Sn at +78°, -320°, and -423°F. Oxygen analyses of the five heats were .09, .11, .15, .17 and .24 weight percent. The data obtained show an increase in tensile and yield strengths at all testing temperatures with an increase in oxygen content. Elongations remained nearly constant except for the .24% O_2 heat at -423°F which exhibited a sharp decrease in elongation. Notched tensile strengths and notched/unnotched tensile strength ratios indicate a high degree of toughness for all of the heats at +78° and -320°F. At -423°F those heats containing under 0.15% oxygen were tough, the heat containing 0.15% oxygen began to show embrittlement due to oxygen, while heats with increasing oxygen contents were progressively more brittle. It is recommended that the oxygen content of the Ti-5Al-2.5 Sn Alloy be limited to a maximum of 0.12% in order to insure adequate toughness for structural applications at liquid hydrogen temperature (-423°F).

Prepared by J. L. Christian
J. L. Christian
Sr. Engineering Metallurgist

Approved by A. Hurlich
A. Hurlich
Research Group Engineer
Materials Research Group

AH:JLC:peg

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FROM: Materials Research Group, 592-1

SUBJECT: Determination of the Effect of Oxygen Content on the Mechanical Properties of Titanium - 5 Al-2.5 Sn Alloy at Room and Cryogenic Temperatures.

INTRODUCTION

The mechanical properties of a large number of titanium alloys have been determined and have been presented in Reports Nos. MRG-189, MRG-213, MRG-246, MRG-249, and MRG-262. Of the alloys investigated the Ti-5Al-2.5 Sn alloy showed the most promise for structural applications at -423°F. It was noted, however, that some heats were appreciably tougher than other heats at extreme sub-zero temperatures. It was felt that the interstitial elements (C, O_2, H_2 and N_2) were responsible for the variations in toughness from one heat to another. The present investigation was made to determine the effect of oxygen content (from 0.09 to 0.24 weight per cent) upon the tensile properties and toughness of the Ti-5Al-2.5 Sn alloy at 78, -320 and -423°F.

MATERIALS

Five heats of Ti-5Al-2.5 Sn alloy containing various amounts of oxygen were supplied by the Titanium Metals Corporation of America. The material was furnished in the form of laboratory rolled sheet 8" x 12" to 16" in size and thicknesses in the range of 0.038" to 0.043". Chemical analyses and some mechanical property data as supplied by Titanium Metals Corporation of America are given in Table 1. Except for the iron in heat V-1670, the Al, Sn, Fe, C, N_2 and H_2 were held at nearly the same level in all five heats. The material was tested in the "as received" (mill-annealed) condition.

PROCEDURE

Blanks for tensile specimens, 9" x 1½", were identified and sheared parallel to the direction of rolling (all specimens tested were longitudinal). Smooth specimens were machined per drawing EMG-D-1 and notched specimens per drawing MRG-D-10, Notch "A". The notched specimens were inspected and notch radii and width between notches measured by an optical comparator. Tests were performed at +78°F (room temperature), -320°F (immersion in liquid nitrogen) and -423°F (immersion in liquid hydrogen). Strain measurements were made by use of extensometers. Strain rates were 0.001"/"/min. up to the 0.2% offset yield point and 0.15"/min. from yield until fracture. Elongations are reported as the total elongation over a 2" gauge length.

RESULTS AND DISCUSSION

The mechanical properties of the five heats of Ti-5Al-2.5 Sn alloy at +78°, -320° and -423°F are reported in Table II. As has been previously experienced, the yield and tensile strengths increase about 100% upon reducing the test temperature from +78° to -423°F. The test temperature appears to have little effect upon the elongation except for the high (0.24%) oxygen heat (V-1671), where the elongation was severely decreased from -320°F to -423°F. The yield and tensile strengths generally increase with increase in oxygen content, which would be expected.

The toughness of the Ti-5Al-2.5 Sn, as evaluated by notched tensile strengths and notched/unnotched tensile strength ratios, is definitely affected by the oxygen content. The notched tensile strength continuously increases with reduction in test temperature for those heats containing 0.09 and 0.11% oxygen (heats V-1699 and V-1668), while the heat containing 0.15% oxygen (heat V-1669) shows only a very slight increase in notched tensile strength between -320°F and -423°F. The heats containing 0.17 and 0.24% oxygen (heats V-1670 and V-1671) show a significant decrease in notched tensile strength as the temperature is reduced from -320°F to -423°F.

Tough, crack-resistant metals show a continuous increase in both smooth and notched tensile strength with decreasing temperature of test. The change in notched tensile test with decreasing temperature, as well as the notched/unnotched tensile strength ratio, may therefore be taken as an index of brittle fracture tendency. The net change in notched tensile strength, between -320°F and -423°F for all heats is plotted against oxygen content in Figure 1. It is seen that at oxygen levels of 0.09 and 0.11%, the notched tensile strength increases approximately 25,000 psi from -320°F to -423°F. At an oxygen level of 0.15%, the increase in notched tensile strength is only 3,000 psi between these two temperatures, while at 0.17 and 0.24% oxygen, the notched tensile strength decreases 18,000 and 40,000 psi respectively between -320°F and -423°F. The smooth curve through these points definitely justifies the 0.12% maximum limit which has been placed upon the oxygen content in General Dynamics/Astronautics Specification No. 0-71010.

The effect of oxygen content upon the notched/unnotched tensile strength ratios at the various test temperatures is shown below:

Oxygen Content Wt. Percent	Notched/ Unnotched +78°F	Tensile Strength Ratio -320°F	(Longitudinal tests) -423°F
.09	1.34	1.25	1.14
.11	1.38	1.27	1.10
.15	1.35	1.24	1.02
.17	1.36	1.23	0.91
.24	1.40	1.17	0.78

RESULTS AND DISCUSSION (continued)

The above data show that oxygen content over the range of 0.09 to 0.24% does not influence the room temperature toughness of the 5Al-2.5 Sn-Ti alloy, as evaluated by means of a notched tensile specimen having a stress concentration factor, K_t, of 6.3. The same test when performed at -320°F begins to show some degradation in toughness at an oxygen level of 0.24% while at -423°F, the notched/unnotched tensile strength drops to unity at an oxygen level of 0.15% and is significantly reduced at higher oxygen contents.

Based upon the results obtained, it is concluded that the specification for 5Al-2.5 Sn-Ti alloy sheet to be used for liquid hydrogen temperature applications should limit the oxygen content to a maximum of 0.12% in order to assure adequate toughness for such applications.

SUMMARY:

1. Yield and tensile strengths of the Ti-5Al-2.5 Sn alloy increase about 100% with decrease in test temperature from 78°F to -423°F.

2. Elongation is only slightly affected by decrease in temp. except for the high oxygen (0.24%) bearing heat. The elongation of this heat is sharply reduced from -320°F to -423°F.

3. The toughness of the Ti-5Al-2.5 Sn alloy, as determined by notched tensile data and notched/unnotched tensile ratios, is definitely affected by increase of oxygen.

4. It is recommended that the O_2 content be limited to 0.10 to 0.12% (0.15% maximum) in order to assure adequate toughness at -423°F.

TABLE 1

Physical Property Data and Chemical Analyses of Ti-5Al-2.5 Sn Alloy*

Heat No.	F_{ty} (Ksi)	F_{tu} (Ksi)	Elong. %	Bend 120° Tr.	Ave. Gauge (in.)	Chemistry (% by weight)**						
						Al	Sn	Fe	C	N_2	O_2	H_2
V-1699	100	113	14	4.0	0.041	5.1	2.8	.07	.03	.01	.09	.014
V-1668	99	112	19	4.0	0.038	5.1	2.6	.10	.03	.02	.11	.009
V-1669	105	114	19	4.0	0.041	5.0	2.5	.07	.03	.02	.15	.009
V-1670	108	117	19	4.0	0.040	5.0	2.6	.02	.03	.02	.17	.011
V-1671	112	123	20	4.0	0.043	4.9	2.5	.07	.04	.02	.24	.010

*Data supplied by Titanium Metals Corporation of America

** Al, Sn, Fe, C, N_2 analyses performed on ingots; O_2, H_2 analyses performed on finished sheet.

TABLE II
Mechanical Properties of Ti-5Al-2.5 Sn Alloy

Heat No.	O_2 Content (%)	Test Temp. (^oF)		F_{ty} (Ksi)	F_{tu} (Ksi)	Elong. (%)	Notched (K_t=6.3) Tensile Strength (Ksi)	Notched/Unnotched Tensile Ratio
V-1699	0.09	78		105	113	16.5	153	
		"		106	115	15.5	155	
		"		–	116	16.5	153	
			Avg.	106	115	16.2	154	1.34
		-320		168	181	16.5	229	
		"		172	184	17.0	227	
		"		167	179	17.0	226	
			Avg.	169	181	16.8	227	1.25
		-423		193	222	14.5	266	
		"		207	224	12.0	248	
		"		195	–	–	248	
			Avg.	198	223	13.3	254	1.14
V-1668	0.11	78		102	111	16.0	155	
		"		102	112	16.5	156	
		"		103	113	17.0	154	
			Avg.	102	112	16.5	155	1.38
		-320		167	179	17.0	230	
		"		167	180	16.0	225	
				169	182	15.0	228	
			Avg.	168	180	16.0	228	1.27
		-423		211	230	18.0	238	
		"		208	228	15.0	267	
		"		199	228	12.5	253	
			Avg.	206	229	15.2	253	1.10
V-1669	0.15	78		105	116	17.0	157	
		"		106	116	17.5	157	
		"		103	115	17.5	156	
			Avg.	105	116	17.3	157	1.35

TABLE II (continued)
Mechanical Properties of Ti-5Al-2.5 Sn Alloy

Heat No.	O_2 Content(%)	Test Temp(^oF)	F_{ty}(Ksi)	F_{tu}(Ksi)	Elong.(%)	Notched (K_t=6.3) Tensile Strength (Ksi)	Notched/Unnotched Tensile Ratio
V-1669	0.15	-320	174	185	14.0	231	
		"	175	186	15.0	232	
		"	172	186	15.5	230	
		Avg.	173	186	14.8	231	1.24
		-423	214	230	13.0	248	
		"	214	231	11.5	226	
		"	213	230	9.5	228	
		Avg.	214	230	11.3	234	1.02
V-1670	0.17	78	107	119	15.5	162	
		"	110	118	16.5	162	
		"	105	116	17.0	160	
		Avg.	107	118	16.3	161	1.36
		-320	176	189	15.0	234	
		"	178	192	15.5	233	
		"	178	192	15.5	234	
		Avg.	177	191	15.3	234	1.23
		-423	226	232	-	214	
		"	226	241	14.5	207	
		"	222	238	10.5	228	
		Avg.	225	237	12.5	216	0.91
V-1671	0.24	78	114	123	16.0	170	
		"	121	122	17.0	172	
		"	115	123	17.0	173	
		Avg.	117	123	16.7	172	1.40
		-320	186	199	14.0	232	
		"	188	201	15.0	238	
		"	191	204	16.0	238	
		Avg.	188	201	15.0	236	1.17
		-423	242	253	4.5	198	
		"	236	249	5.0	209	
		"	237	255	-	180	
		Avg.	238	252	4.8	196	0.78

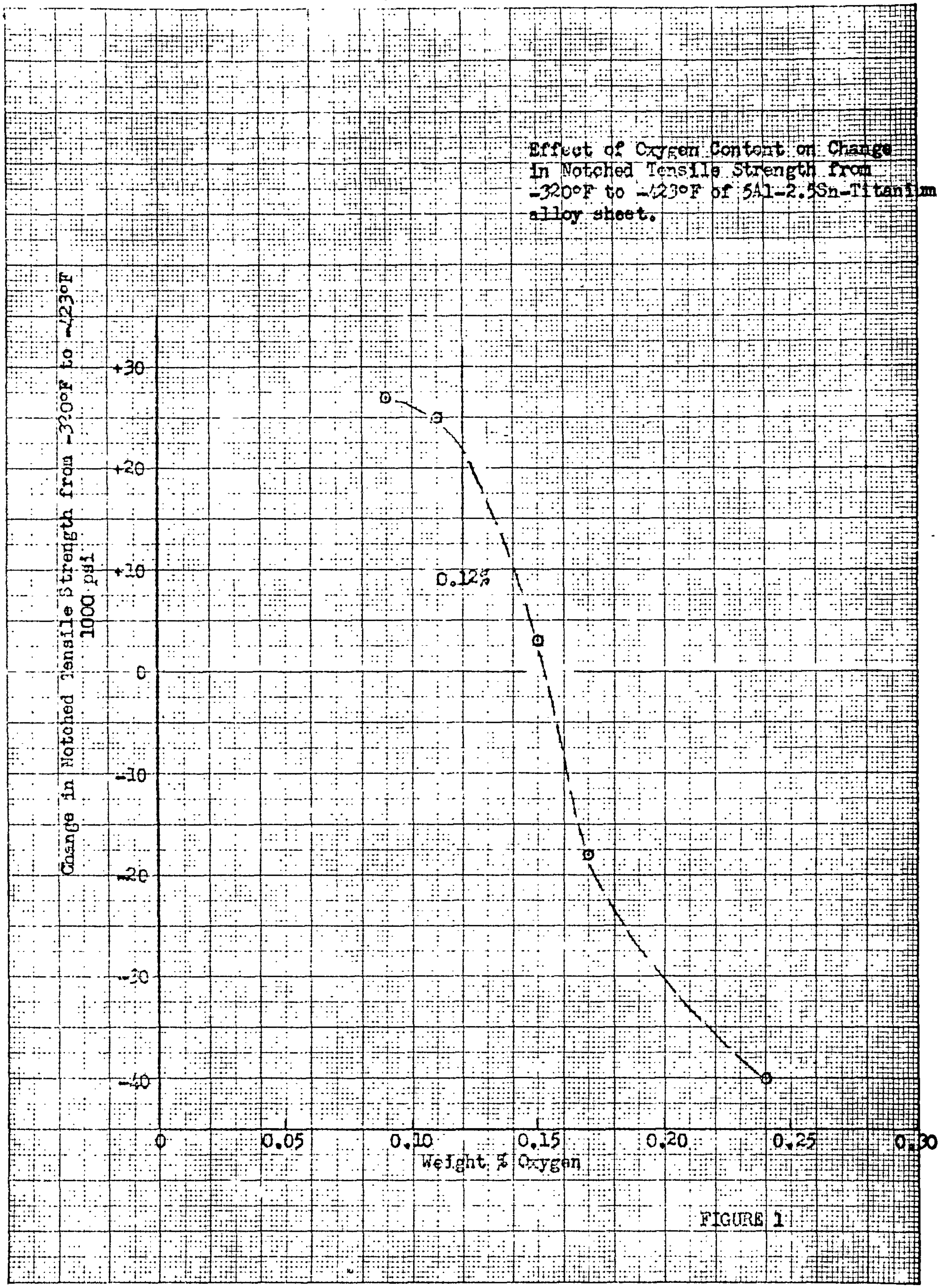

FIGURE 1

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Section 2 - Mechanical Properties of Non-Metals

22 June 1961

SUBJECT: Tensile Testing of Adlock 851, Adlock PG-LA and Adlock EG-11A-81A from -423°F to 78°F.

ABSTRACT: Ultimate tensile strength, initial and secondary tensile modulus, and proportional limit were determined for Adlock 851, Adlock PG-LA and Adlock EG-11A-81A at 78°, -100°, -320° and -423°F. Ultimate tensile strength for Adlock 851 increased from 39,240+ psi at 78° to 75,750 psi at -423°F. Adlock PG-LA showed an increase in ultimate tensile strength from 46,070 psi at 78° to 84,910 psi at -423°F while the ultimate tensile strength of Adlock EG-11A-81A increased from 32,460 psi at 78° to 51,110 psi at -423°F.

Prepared by J. Hertz
J. Hertz

Approved by A. Hurlich
A. Hurlich
Research Group Engineer
Materials Research Group

AH:JH:bts

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FROM: Materials Research Group, 592-1

SUBJECT: Tensile Testing of Adlock 851, Adlock PG-LA and Adlock EG-11A-81A from -423°F to 78°F.

INTRODUCTION

There has developed an increasing requirement for structural plastics in cryogenic environments. There is a definite lack of data available in the existing literature on the tensile properties of structural plastics at -320° and -423°F. In order to supplement existing data, tensile properties were run on three structural plastics at 78°, -100°, -320° and -423°F. The materials investigated were Adlock 851, Adlock EG-11A-81A and Adlock PG-LA.

DISCUSSION

The three materials investigated are products of the American Reinforced Plastics Company, Los Angeles, California. Adlock 851 is a phenolic resin impregnated on style 181 fiberglass cloth, Adlock PG-LA is a polyester impregnated 181 fiberglass cloth and Adlock EG-11A-81A is an epoxy impregnated 181 fiberglass cloth. All three are supplied as "B-staged" materials. Test samples were supplied by the American Reinforced Plastics Company per specifications of the General Dynamics/Astronautics' Materials Research Group (see Figure 1).

The tensile coupons were cut from laminates made of 12 plies of "B-staged" 181 glass cloth having an A-1100 finish in the case of Adlock 851 and a Volan A finish in the other two cases. Reported values for resin content, resin flow, volatile content are tabulated in Table I along with pressure and cure cycle utilized in making the laminates. In each case fabrication consisted of a lay-up of the 12 plies in a longitudinal direction on a caul plate and vacuum bagging at 12 - 14 psi. Doublers were bonded to the specimens utilizing a room-temperature curing epoxy-polyamide adhesive. In addition to the bond, four screws were utilized with each set of doublers. This configuration eliminated most of the bearing type failures experienced when testing Conolon 506 (see MRG 120). Bearing failures were experienced in a few cases when the screws were undersize.

Average values for ultimate tensile strength, initial modulus of elasticity in tension, initial proportional limit and secondary modulus of elasticity in tension are tabulated in Tables 2 - 4. For comparison purposes data obtained on Conolon 506 and previously reported is included (see Table 5).

In general there was little scatter in the ultimate tensile strength data. However, the initial modulus and proportional limit data did show considerable scatter particularly at -320° and -423°F. Secondary modulus data was very

consistent. In a few cases initial modulus values were lower than secondary modulus values. There is no explanation for this phenomena at present.

There was good agreement between the ultimate tensile values obtained with Conolon 506 and Adlock 851 (both phenolic-fiberglass laminates). Modulus values were considerably higher for the Conolon 506 laminates while the proportional limit values were considerably higher for the Adlock 851 laminates. The ultimate tensile strength values for the polyester-fiberglass laminate were higher than for both phenolic-fiberglass laminates. Modulus values were comparable to those obtained with Conolon 506. The values obtained with the epoxy-fiberglass laminate were disappointing. It is believed that this may be a result of poor fabrication since thickness measurements were approximately 0.170 for a 12 ply laminate as compared to approximately 0.125 for the other materials investigated. It appears that there must have been a loss of vacuum during the curing operation. This would result in insufficient resin flow which in turn would result in a thicker laminate having poorer tensile strength and modulus properties. Most epoxy systems are not recommended for vacuum bagging, and it is possible that vacuum was maintained throughout the curing cycle but the pressure was not high enough to cause sufficient flow.

TABLE 1

Properties and Curing Conditions for "B-Staged" Materials

Material	Resin Content, %	Resin Flow, %	Volatiles, %	Curing Pressure	Cure Cycle
ADLOCK 851	41.5	26.8	7.1	12-14 psi	½ hr. at 200°F ½ hr. at 250°F ½ hr. at 300°F 3½ hrs. at 350°F
ADLOCK PG-LA	39.1	14.1	3.5	12-14 psi	½ hr. at 280°F
ADLOCK EG-11A-81A	41.0	17.6	4.74	12-14 psi	½ hr. at 340°F post cure: ½ hr. at 300°F ½ hr. at 400°F

TABLE 2

Tensile Properties of Adlock 851

	Ultimate Tensile Strength psi	Initial Modulus of Elasticity psi x 10^6	Proportional Limit psi	Secondary Modulus of Elasticity psi x 10^6	
78°F	40,480	2.98	15,880	2.11	
	40,070	-	-	-	No Graph
	41,390	3.03	19,400	2.16	
	34,410+	3.16	18,720	2.11	Failed in bearing & repulled
	39,840	2.93	18,050	2.16	
Avg.	39,240+	3.03	18,020	2.14	
-100°F	40,970	2.44	21,860	1.55	
	42,690	3.08	20,730	1.66	
	55,420	3.27	23,530	1.68	
	41,370	3.19	23,420	1.53	
Avg.	45,110	3.00	22,390	1.61	
-320°F	65,200	3.17	21,120	1.69	
	68,540	3.29	18,310	1.77	
	73,250	3.06	19,800	1.62	
	73,150	2.98	19,250	1.60	
	64,800	2.96	20,580	1.62	
Avg.	68,990	3.09	19,810	1.66	
-423°F	75,430	2.95	21,810	1.61	
	74,390	2.55	22,030	1.44	
	75,020	2.64	22,730	1.81	
	76,820	2.45	21,380	1.75	
	77,110	2.92	23,160	1.78	
Avg.	75,750	2.70	22,220	1.68	

TABLE 3

Tensile Properties of PG-LA

	Ultimate Tensile Strength psi	Initial Modulus of Elasticity psi x 10^6	Proportional limit psi	Secondary Modulus of Elasticity psi x 10^6
78°F	45,630	3.15	7,450	2.33
	43,500	3.31	5,560	2.33
	49,610	2.92	6,080	2.40
	45,130	3.50	6,880	2.32
	46,460	3.32	7,970	2.46
Avg.	46,070	3.24	6,790	2.37
-100°F	63,830	3.19	7,560	2.44
	52,110	2.98	17,880	3.49
	63,170	3.66	16,710	2.42
	60,820	3.86	24,300	2.45
	66,740	3.27	6,540	2.31
Avg.	61,330	3.39	14,600	2.62
-320°F	65,040+	3.24	7,210	2.48 Bearing Failure
	78,150+	-	-	2.00 Bearing Failure
	62,390+	3.19	14,590	2.64 Bearing Failure
	81,800	5.54	12,930	2.83
	81,300	4.24	9,440	2.60
Avg.	73,730+	4.05	11,040	2.51
-423°F	82,930	3.82	12,170	2.69
	85,050	5.75	11,580	2.64
	87,620	1.92	16,830	2.48
	83,940	2.69	9,640	2.40
	85,030	4.08	8,490	2.72
Avg.	84,910	3.65	11,740	2.59

TABLE 4

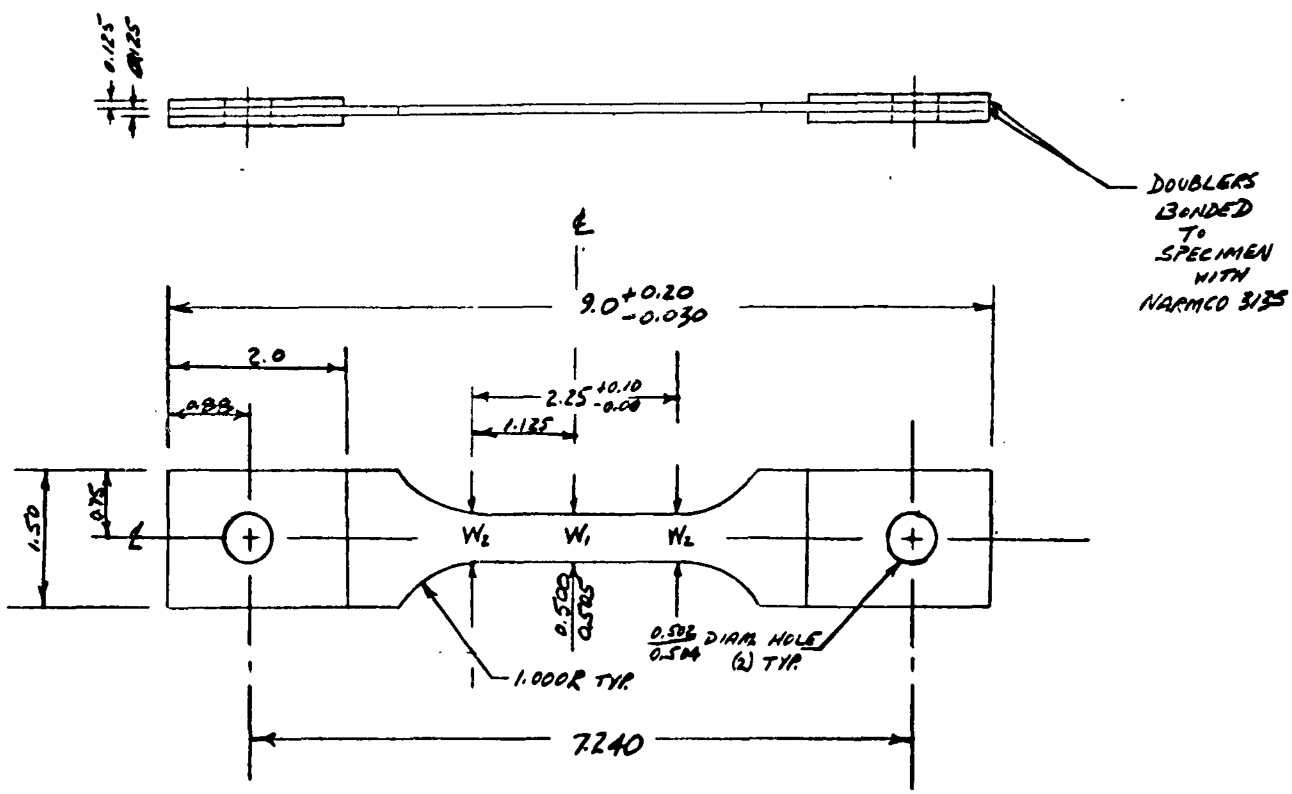
Tensile Properties of Adlock EG-11A-81A

	Ultimate Tensile Strength psi	Initial Modulus of Elasticity psi x 10^6	Proportional Limit psi	Secondary Modulus of Elasticity psi x 10^6
78°F	29,080	2.22	12,840	2.00
	33,080	2.64	7,250	2.26
	33,670	2.51	7,130	1.93
	33,010	2.32	9,300	1.86
	33,440	2.82	10,360	2.49
Avg.	32,460	2.50	9,380	2.11
-100°F	33,070	3.14	15,500	1.88
	31,470	2.53	13,330	1.83
	46,670	2.46	17,570	2.09
	48,590	1.78	10,860	2.00
	45,620	2.30	14,980	1.77
Avg.	41,080	2.44	14,450	1.91
-320°F	56,530	2.28	17,390	2.17
	47,730	-	-	1.87
	62,510	2.97	18,020	1.88
	64,610	3.70	16,910	2.08
	61,650	2.87	14,850	1.86
Avg.	58,610	2.96	16,790	1.97
-423°F	51,170	1.95	12,820	1.56
	52,410	2.43	14,770	1.82
	54,540	2.05	13,690	1.74
	51,750	2.52	13,890	1.76
	45,690	2.15	15,130	1.83
Avg.	51,110	2.22	14,060	1.74

TABLE 5

Tensile Properties of Conolon 506

	Ultimate Tensile Strength psi	Initial Modulus of Elasticity psi x 10^6	Proportional Limit psi	Secondary Modulus of Elasticity psi x 10^6	
78°F	46,090	3.63	8,140	2.52	
	43,190	3.38	9,400	2.49	
	46,170	3.51	10,050	2.68	
	44,410	3.48	9,850	2.54	
	42,060	3.34	9,330	2.51	
Avg.	44,380	3.47	9,440	2.55	
-100°F	64,200+	4.97	17,110	2.97	Bearing Failure
	70,260	4.33	12,490	2.86	
	70,750+	5.23	14,970	2.61	Bearing Failure-repulled
	59,950+	4.11	14,990	2.60	Bearing Failure
	58,490+	4.66	12,980	2.69	Bearing Failure
Avg.	64,730+	4.66	14,510	2.75	
-320°F	73,760	3.46	13,080	2.23	
	59,420	3.49	20,770	3.02	
	68,180	3.81	14,200	2.60	
	79,620+	3.56	16,520	2.43	Bearing Failure
	52,310+	-	-	-	Bearing Failure
Avg.	66,660+	3.58	16,140	2.57	



Gradual Taper from W_2 to W_1 of 0.005 $^{+0.000}_{-0.002}$.

Figure 1

TENSILE TEST SPECIMEN

Section 3 - Physical Properties of Metals

CONVAIR ASTRONAUTICS

SUBJECT: X-Ray Diffraction Substantiation of Magne-Gage Determinations of Martensite Composition in 301 Stainless Steel.

ABSTRACT: X-ray diffraction was used as a means of measuring the relative amounts of martensite in 301 stainless steel samples. The primary object of the investigation was to substantiate readings taken on the calibrated Magne-gage.

A spinning sample holder is shown and explained and the reasons for using it on 301 are discussed.

Prepared by M. D. Campbell
M. D. Campbell

Approved by A. Hurlich
A. Hurlich
Research Group Engineer
Materials Research Group

AH:MDC:jml

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TO: Distribution

FROM: Materials Research Group, 592-1

SUBJECT: X-ray Diffraction Substantiation of Magne-Gage Determinations of Martensite Composition in 301 Stainless Steel.

INTRODUCTION:

The work reported was part of an over-all program to establish a method of measuring the absolute percentage of the martensite phase in 301 stainless steel. A Magne-gage had been calibrated to read this percentage by using powder mixtures of various known compositions as calibration standards. The compositions of several unknown samples, including the ones used in this study, were then determined by the density method (1) and by the visual counting method.(2) Magne-gage readings were then taken on these samples, and the readings were plotted on the Magne-gage curves at the compositions determined by the above methods. Correlation was good, then, if these points fell on the calibration curves.

As a further check of the calibration of the Magne-gage, it seemed desirable to use the ratio of the diffracted x-ray intensity from the martensite to that from the austenite in each sample as a quantitative indication and to plot these ratios as a function of composition as determined by the Magne-gage. If anything but a smooth continuous curve were obtained, the correlation would not be considered good and the reason for this would have to be determined.

The use of an x-ray diffractometer to determine the quantity of the martensite phase in 301 stainless steel is hampered by preferred orientation of this phase. There are two problems, the first of which is illustrated in Figures 1-a and 1-b.

(1) The theoretical density of the constituents is calculated and the amount of each determined from a bulk density measurement.

(2) Samples are electro-polished and etched. The surface of the sample is then visually inspected under a microscope and the percentage of martensite grains seen is recorded.

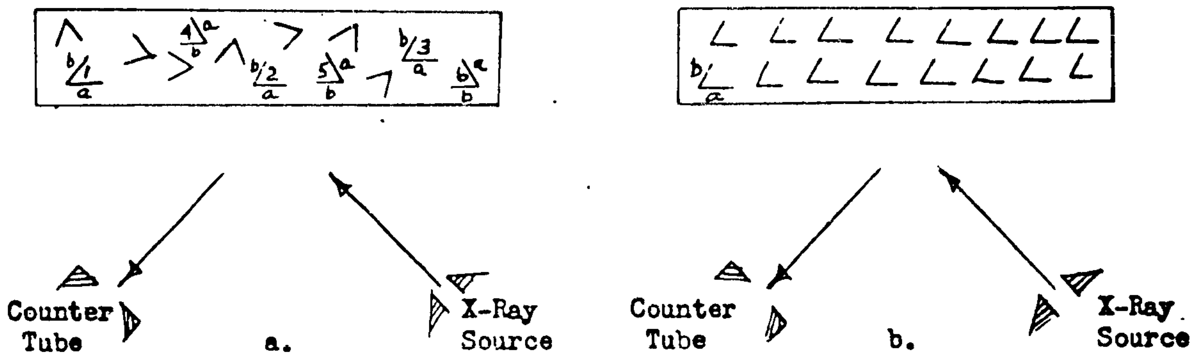


FIG. 1

Figure 1-a represents a sample free of preferred orientation in the two dimensions shown. It can be seen that the "a" and "b" directions (the only two shown) in each grain are randomly oriented. With the geometry established for an ordinary diffractometer where the angle the beam makes with the face of the sample is always equal to the angle between the line-of-sight of the counter and the face of the sample, the only planes in the sample which can give rise to a diffraction are those which are parallel to the surface.(3) Therefore, grains 1, 2 and 3, Figure 1-a, are in position to allow deffraction from "a" planes that the counter will see and grains 4, 5 and 6 will allow recorded diffraction from the "b" planes. It can be assumed that a randomly oriented sample will have a number of grains with the appropriate planes parallel to the surface to enable the counter to pick up all possible diffractions in the type of crystal being studied.

Figure 1-b shows a sample with a high degree of preferred orientation. When this sample is scanned, the "a" peak will be seen when the proper beam angle is reached. The "b" diffraction will never be seen, however, because there are no grains with the "b" planes parallel to the surface.

(3) See Figure I. Since the beam must strike a set of planes at an angle θ_1 which satisfies $n\lambda = 2\,d \sin \theta_1$ for diffraction to take place, if, at some time during the scanning of the sample, θ_2, the angle the beam makes with the sample, minus α , the angle the planes make with the surface, equals θ_1 then diffraction will take place but it will not be seen by the counter tube. In a sample with no preferred orientation, there are enough randomly oriented grains to give rise to all possible diffractions continually but these do not contribute to the pattern recorded unless the grains are parallel to the surface.

If, then, the grains represented by planes "a" and "b" in figure 2 represent martensite in the samples and the diffractions from the "a" planes are used as a relative measure of the percentage of martensite in the samples, the results have little meaning. Sample "b" could contain 100% martensite and still give no intensity on the peak being used as a measure of the quarterly of that phase.

The second problem is due to the actual shape of the martensite grains in 301 stainless steel. Figures 3-a and 3-b represent the positions of the long thin martensite grains in a random sample and a preferentially oriented sample.

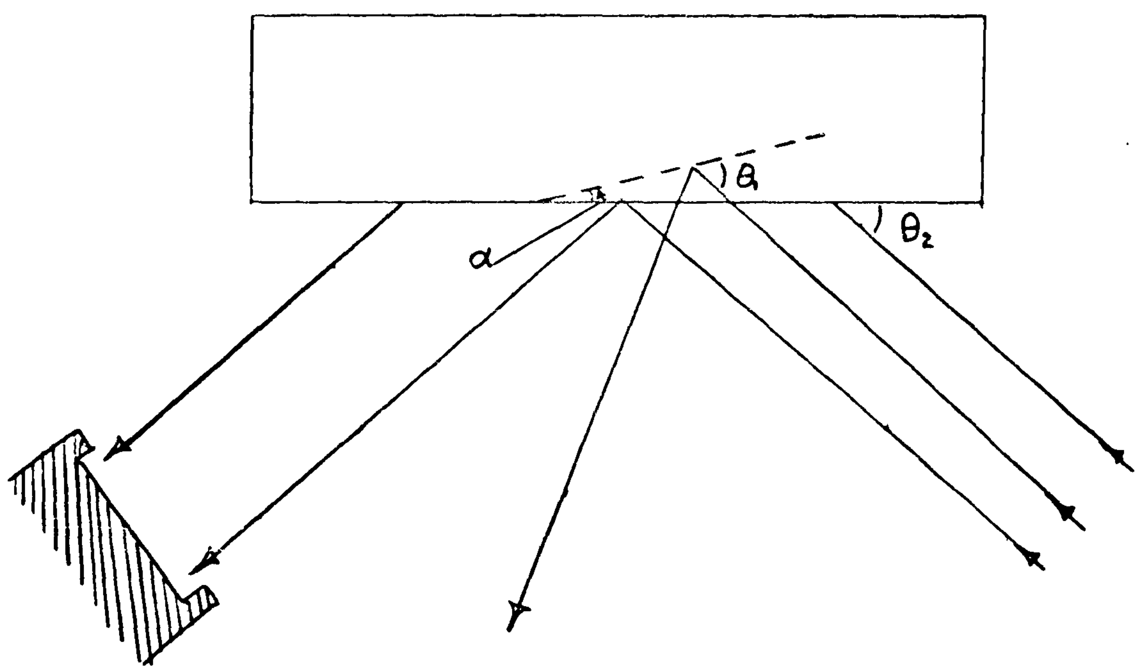
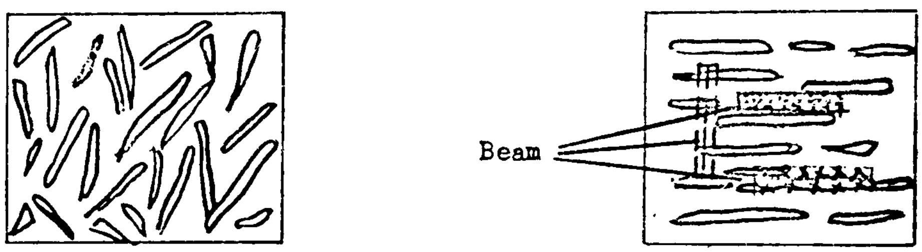


FIGURE I

The X-ray beam on most commercial diffractometers consists of a narrow, broken, vertical rectangle. The results of the combination of a narrow beam (quite necessary for resolution) and long, thin grains are shown in Figure 4.



a b

FIG. 3

If the beam were to strike the dotted area, (Fig. 3-b) it would see very little martensite, whereas the dashed area would include a large amount, and that represented by X's would include still more. Compare this to Figure 4-a where the beam would see a homogeneous density of martensite in any position. Again, the method of using measured diffraction intensity as a quantitative indication is not reliable if this situation exists.

The problem of having a large number of grains with the planes in question not parallel to the surface cannot be over come on the diffractometer. Several things can be done to get around it, though, their success depending on the samples used. Briefly, these are assuming that the samples have the same degree of preferred orientation or plotting pole figures (4) to find a set of planes which shows little or no preferred orientation in all samples to be compared. The second is more exact and reliable but takes a number of hours per sample. The first can be used if enough is understood about the degree and type of preferred orientation in the samples.

Therefore, if either of the above methods is used to allow the assumption that the samples have the same degree of preferred orientation with respect to the planes used, the intensities of the diffractions from a particular set of planes can be used as a relative measure of the amounts of martensite present, providing that the second problem discussed is overcome.

(4) See Sproull, X-Rays in Practice, McGraw Hill, 1946

Rapid rotation of the sample about an axis perpendicular to its face will accomplish this by allowing the counter to see an average martensite density. This was the approach used here.

SAMPLES:

Six 301 stainless steel samples cut from a piece which had been bent in liquid nitrogen were supplied by J. Christian. These were mounted and electro polished.

The compositions of the six had been determined by use of the Magne-gage which had been calibrated with powder standards.

METHOD:

A standard X-ray diffraction technique was used on the General Electric XRD-5 (5) with the flat sample holder replaced by a modified General Electric powder sample spinner. Figure 4 shows the spinner before and after modification. The shaft was lowered so that the beam would hit the sample on the axis of rotation and a new shaft assembly was made to allow samples of various thicknesses to be used. Since it is mandatory that the X-ray beam and the line-of-sight from the counter intersect at the face of the sample, a square was made which fits over the slit system and locates this point. The shaft is then adjusted to bring the face of the sample up to it. Figure 5 shows the square in position.

A diffractometer trace was made on each sample, with the spinner revolving at about 160 rpm, so that the 211 martensite and the 220 austenite peaks could be located exactly. Once they were located, the diffractometer was set on each peak and the absolute intensity was recorded. The average background in the vicinity of the two peaks was also measured in each sample and subtracted from the absolute intensities of the peaks. The corrected intensity of the 211 martensite was then divided by that of the 220 Austenite in each case. These ratios are shown in Table I.

RESULTS AND CONCLUSIONS:

Figure 6 shows a plot of two sets of peak ratios vs. analysis as supplied with the samples. It can be seen that the points fall on a fairly smooth curve except for those for sample # 1198-B-7, 64.5% martensite. It should be remembered that the "known" compositions of the samples were obtained by Magne-gage readings. It is supposed that the Magne-gage readings are not affected by quantity or quality of prepared orientation but, as explained above, the X-ray measurements are. In order to explain the great deviation

(5) Tube: Cr, Voltage: 45KV, Current: 18 ma, Filter: .001" V.

of # 1198-B-7 from the general curve, it was first thought the degree of preferred orientation was considerably different in this sample which would not allow the ratio obtained from it to be compared to the others.

It was eventually learned, however, that the six samples had all been re-polished several times between the Magne-gage readings and the X-ray measurements. It has been shown previously that there is, in general, a phase composition gradient through 301 samples where the martensite has been formed by mechanical deformation. Therefore, since the X-rays see a small depth of the sample, readings would be different after surface removal.

When this was pointed out, all six samples were re-run on the Magne-gage and the X-ray peak ratios re-plotted vs. the new compositions readings. (See Figure 7). It is interesting to note the changes recorded in Table I. Of most interest was the change in sample 1198-B-7 from 64.5% to 14% which brings the plotted point considerably more in line with the others.

It would seem, then, that the X-ray results obtained by spinning the samples fall close enough to a smooth curve to indicate that the Magne-gage readings give a reasonable indication of the Martensite compositions. To make this conclusion, however, it must be assumed that all samples had the same magnitude of preferred orientation. On the basis of this assumption the deviations from the curve can be attributed to the spread in degree of prepared orientation of the samples.

TABLE I

SAMPLE	ORIGINAL COMP. % MART.	X-RAY RATIO RUN 1	X-RAY RATIO RUN 2	RE-RUN COMP. % MART.
579-C	45.8	.40	.51	50.0
1198-B-7	64.5	.058	.085	14.0
1199-C-8	95.1	3.55	3.31	93.0
1189-B-4	2.7	.015	- --	0.0
1192-B-7	10.3	.10	- --	6.0
1196-B-1	12.2	.13	.16	6.0

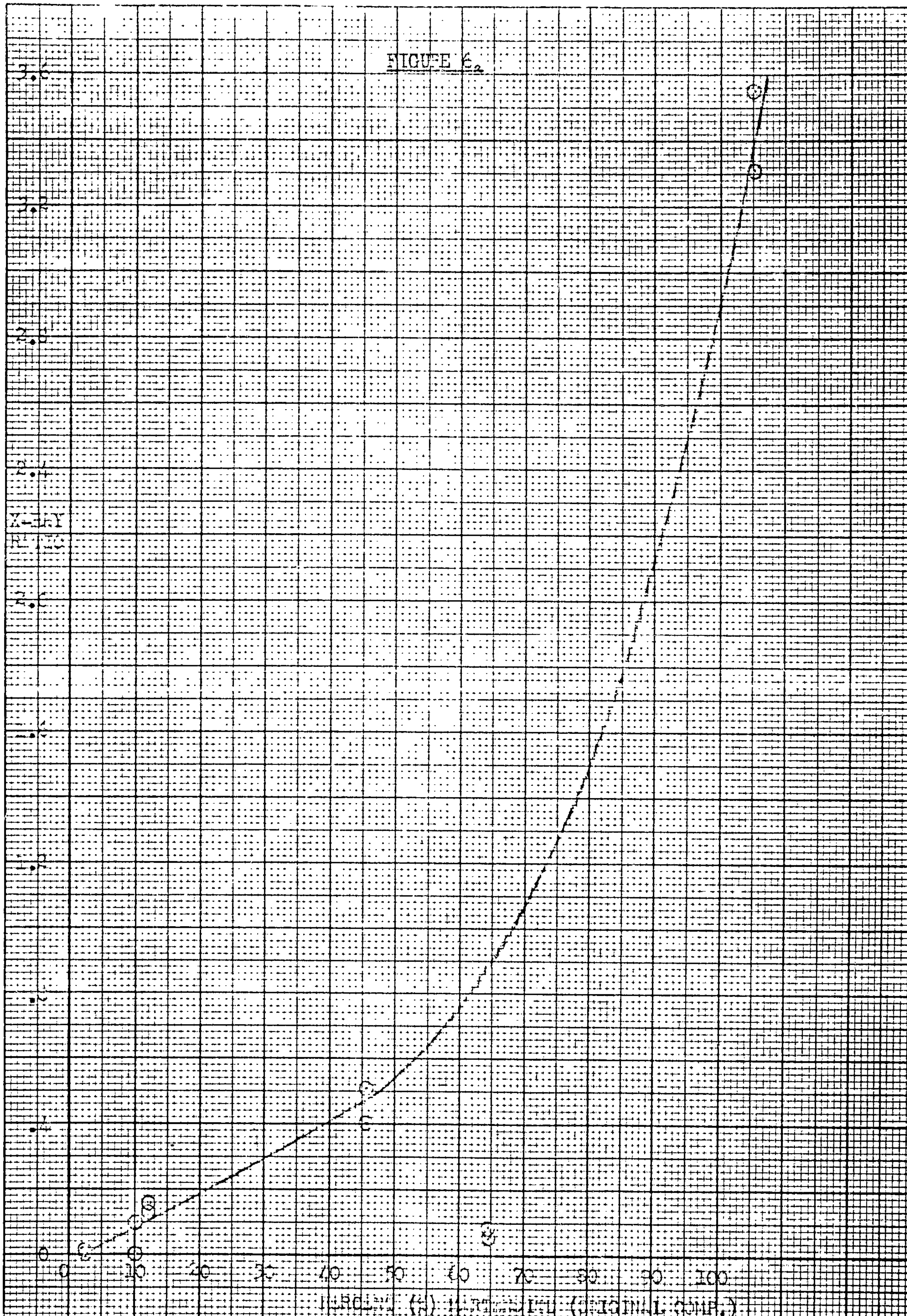


FIGURE 6a
0
10
20
30
40
50
60
70
80
90
100

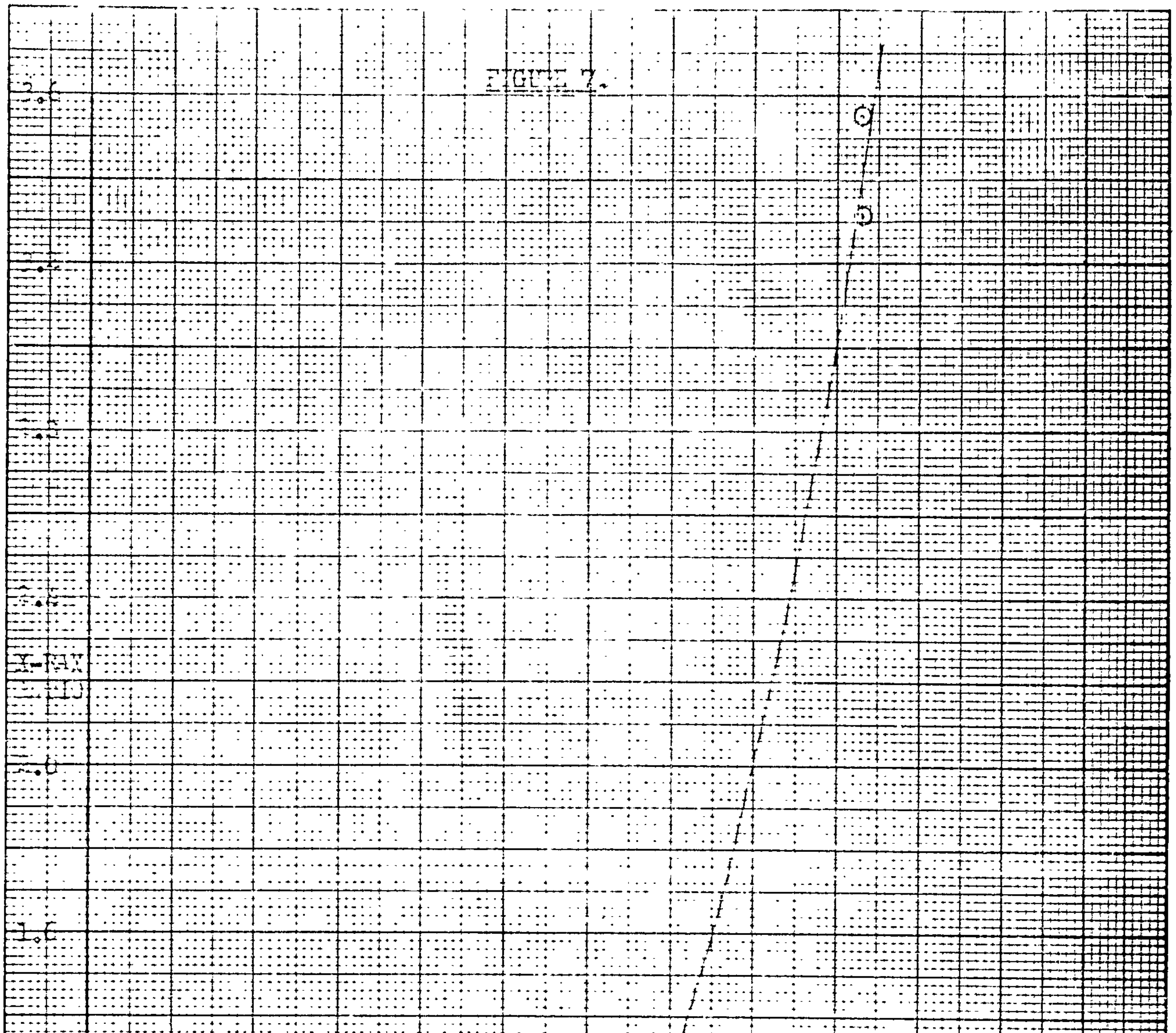


FIGURE 7.
Y-MAX
0
10
20
50
70
100

Section 4- Physical Properties of Non-Metals

SUBJECT: **Measured Values for the Coefficients of Linear Expansion of Polycel 420 and Conolon 506 at Low Temperatures**

ABSTRACT

The coefficients of expansion of Polycel 420 and Conolon 506 have been measured at low temperatures, down to -250° F, using a modified Leitz Dilatometer. The Polycel is expanding and contracting at only 60 percent of the rate of Conolon 506. The average coefficient of expansion of Conolon 506 is 4.8×10^{-6} in./in./°F from room temperature down to -250° F. Over the same temperature range the coefficient for Polycel 420 is 3.1×10^{-5} in./in./°F. The contraction of Polycel below -180° F is greatly reduced due to the freezing of Freon.

Prepared by: J. F. Haskins
J. F. Haskins

Approved by: A Hurlich
A. Hurlich
Research Group Engineer
Materials Research Group

AH:JFH:mj
Distribution:
- K. A. Ehricke, 100-0
- H. F. Dunholter, 590-0
- W. F. Radcliffe, 595-0
- F. C. Rosacker, 541-7
- C. Pruckner, 541-3
- R. S. Shorey, 597-3
- W. B. Mitchell, 595-1
- E. Haupt, 541-7
- R. W. Norris, 541-3
- A. Vinzant, 535-5
- A. Fullarton, 454-0
- E. Schwartz, 595-1
- J. C. Ballinger, 595-1

TO: Distribution

FROM: Materials Research Group

SUBJECT: Measured Values for the Coefficients of Linear Expansion of Polycel 420 and Conolon 506 at Low Temperatures

INTRODUCTION

The use of polyurethane foams along with phenolic-fiberglas laminates as cryogenic insulations has made it necessary to have a more thorough understanding of their thermal properties. The coefficients of linear expansion for these materials have been investigated from room temperature down to -250° F. These measurements were made using a Leitz Dilatometer which has been modified for low-temperature work. This information is presented in graph form in this report.

MATERIALS MEASURED

Polycel 420 is a 2 lb/ft^3 Freon-blown polyurethane foam produced by the Polytron Corporation, Richmond, California. It is a rigid foam having approximately 96 percent closed cells.

Conolon 506 is a high-temperature phenolic-fiberglas laminate produced by Narmco Resins and Coatings, Inc., Costa Mesa, California. It conforms to MIL-R-9299, Type II, Class I. The laminate tested consisted of 12 plies of "B-staged" 181 glass cloth having a Volan A finish. The "B-staged" cloth had a resin content of 34.9 percent and a volatile content of 7.7 percent. The laminate was vacuum bagged at 29 in. Hg, and subjected to the recommended cure cycle.

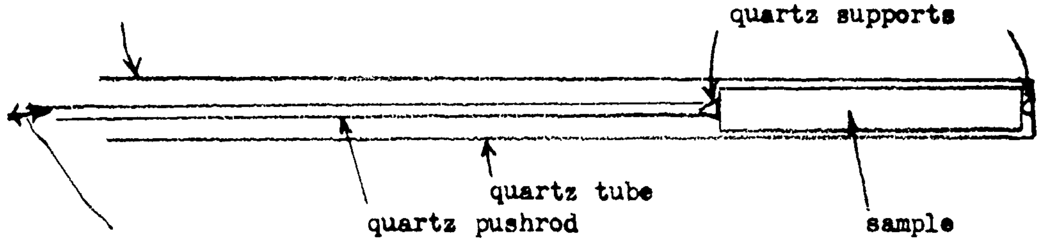
EQUIPMENT

The standard Leitz Dilatometer measures the coefficient of linear expansion either by comparing dimension change of a test body to that of a standard body or by recording dimension change on a previously calibrated scale. This instrument is usually used at elevated temperatures by placing a tube furnace around the sample. Low temperatures were achieved by placing a liquid nitrogen jacket around the sample. The dimensions of the liquid nitrogen jacket were similar to those of the furnace.

The sample holder is constructed of concentric quartz tubes so that any expansion of the quartz is canceled except for the actual sample length. Thus, for single holder operation one measures the dimensional change due to the difference between quartz and the sample. The differential measurement is made by using two sample holders placed side by side. One holder contains a

standard body and the other contains the sample. This measurement records the actual difference in expansion between samples. The expansion of the quartz is completely canceled. Fused quartz has a very low coefficient of expansion; i.e., 0.25×10^{-6} in./in./°F. For materials such as polyurthane foams where the expansion is large this would amount to less than a 1-percent error. In Conolon 506 this effect could cause an error of about 5 percent. These errors were not corrected out.

Figure 1



EXPERIMENTAL RESULTS

The curve shown in Figure 2 shows the coefficient of linear expansion of Conolon 506 as a function of temperature. If a correction were applied for the expansion of the fused quartz, the experimental portion of the curve would be raised. This would make the room temperature measured value agree with the literature values.

The Polycel 420 was measured under the following conditions:

1.	Evacuated and purged with dry nitrogen	Figure 3
2.	Dry helium atmosphere - atmospheric pressure	Figure 4
3.	Atmospheric pressure - air	Figure 5
4.	Vacuum (10-micron)	Figure 7

In Figures 5 and 7 two samples were measured in order to give some idea of variation between pieces. These samples were both cut from the same block of material.

The data were taken as the sample was cycled from room temperature to -250° F and back. A typical cooling and heating curve of this type shows a definite hysteresis. See Figure 6.

Cooling rates in these measurements were not found to be important, but were about 150° F/hr. The density of the Polycel 420 was found to be 1.84 lb/ft^3.

CONCLUSIONS

The average coefficient of expansion of Conolon 506 from room temperature down to -250° F is 4.8 x 10^{-6} in./in./°F and the average coefficient of linear expansion of Polycel 420 over the same temperature range is 3.1 x 10^{-6} in./in./°F. The Polycel expands or contracts at only 60 percent of the rate of Conolon 506.

All of the contraction curves for Polycel seem to level off below -180° F except for the helium atmosphere. This leveling off point occurs at a temperature near the freesing point of Freon (-170° F).

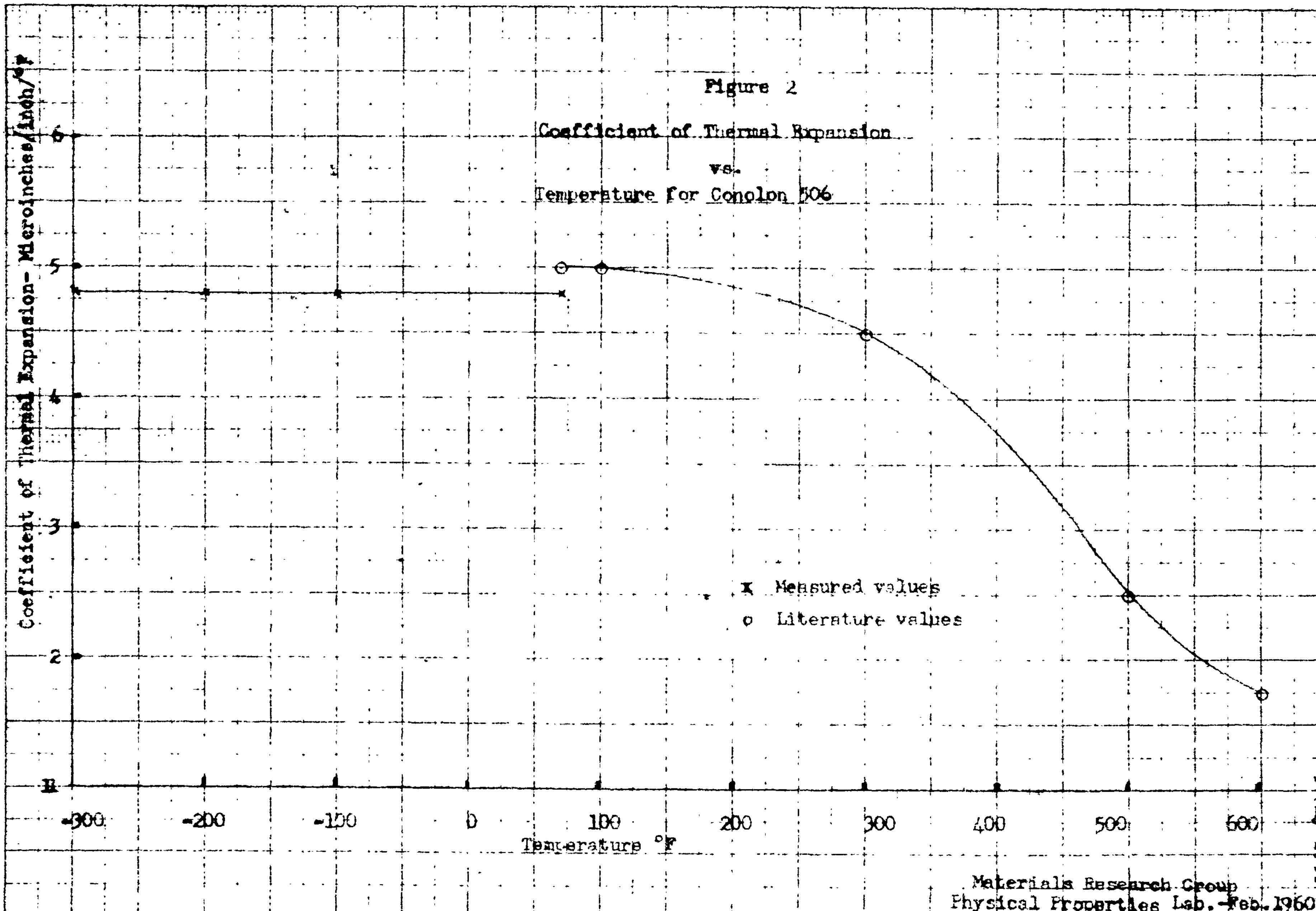


Figure 2

Coefficient of Thermal Expansion

vs.

Temperature for Conolon 506

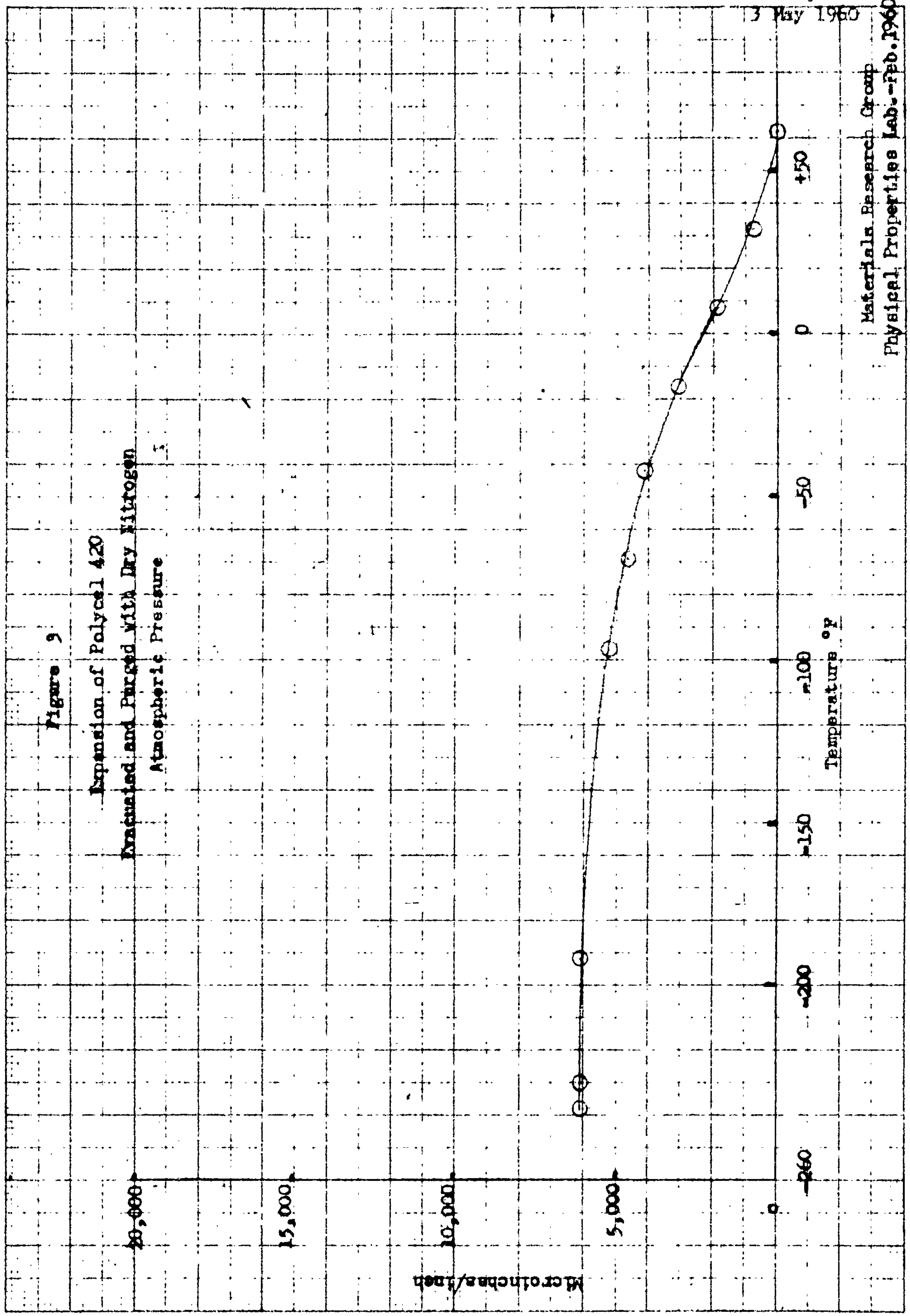


Figure 9
Expansion of Polycel 420
Evacuated and Purged With Dry Nitrogen
Atmospheric Pressure
Microinches/Inch
20,000
15,000
10,000
5,000
0
+50
0
-50
-100
-150
-200
-250
Temperature °F
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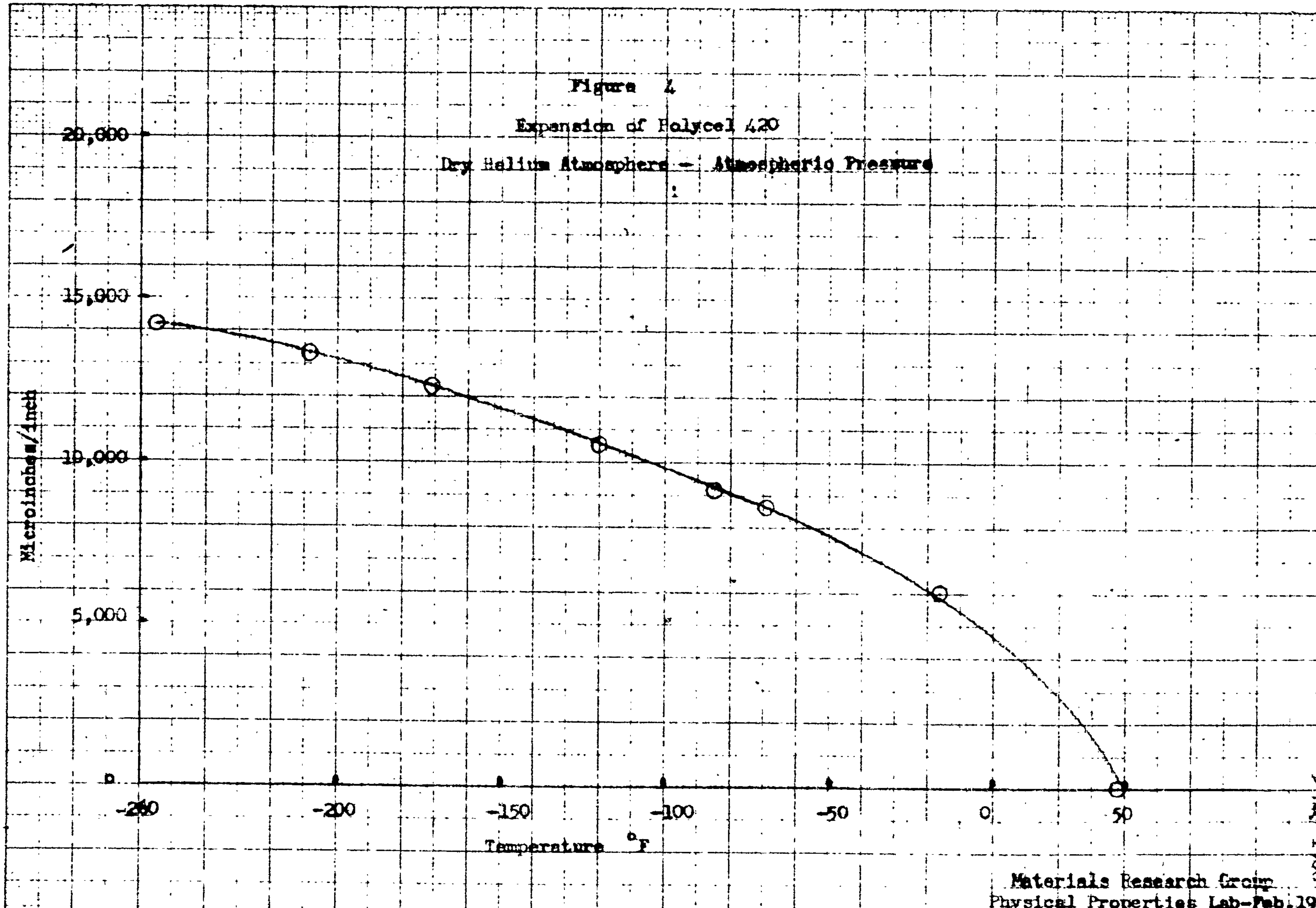
K+E 10 X 10 TO THE 1/2 INCH 359T-11
KEUFFEL & ESSER CO.
ALBANENE



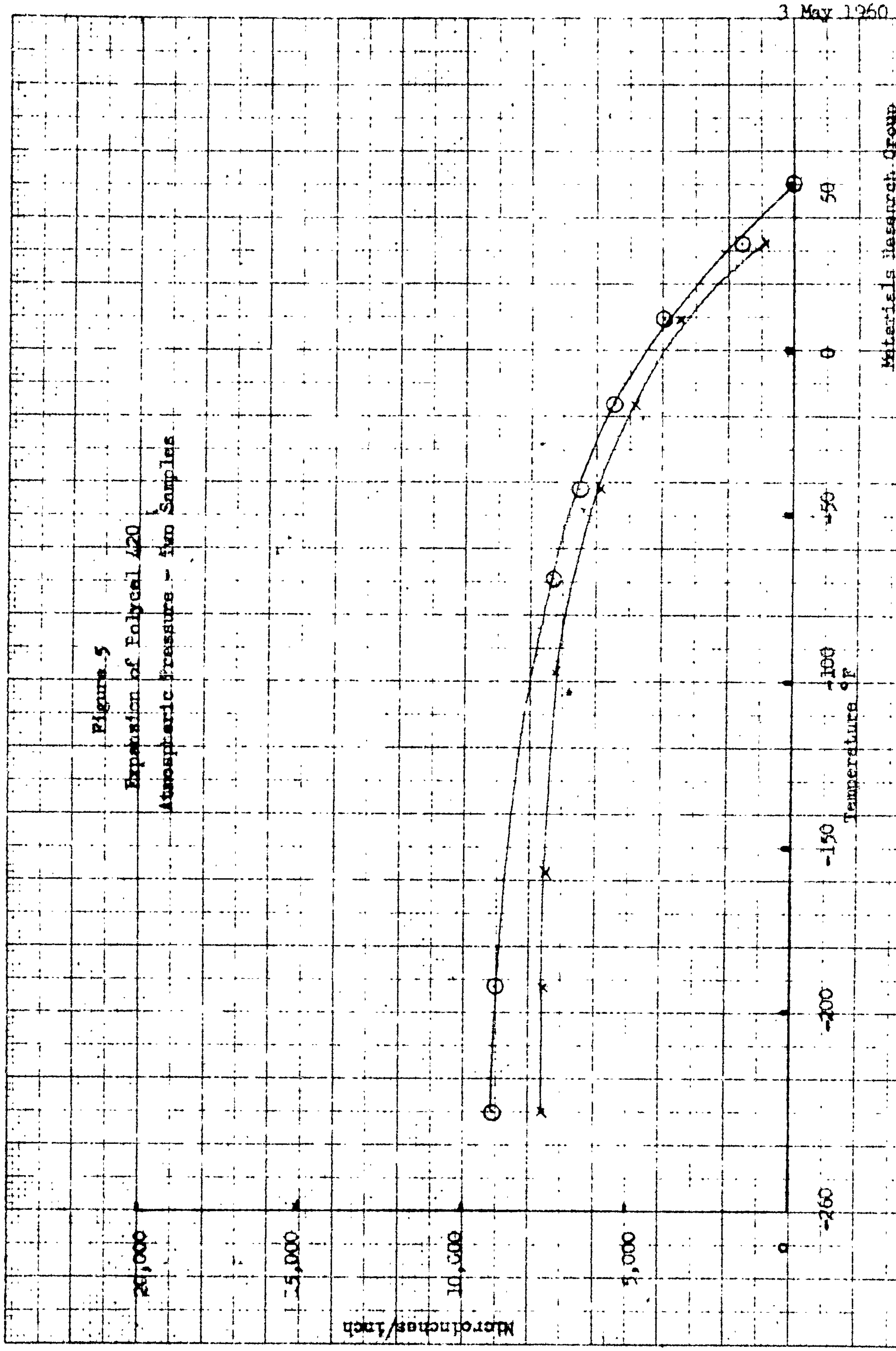


Figure 5
Expansion of Polycal 420
Atmospheric Pressure - Two Samples
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Temperature °F
Microinches/Inch
20,000
15,000
10,000
5,000
0
-250
-200
-150
-100
-50
0
50

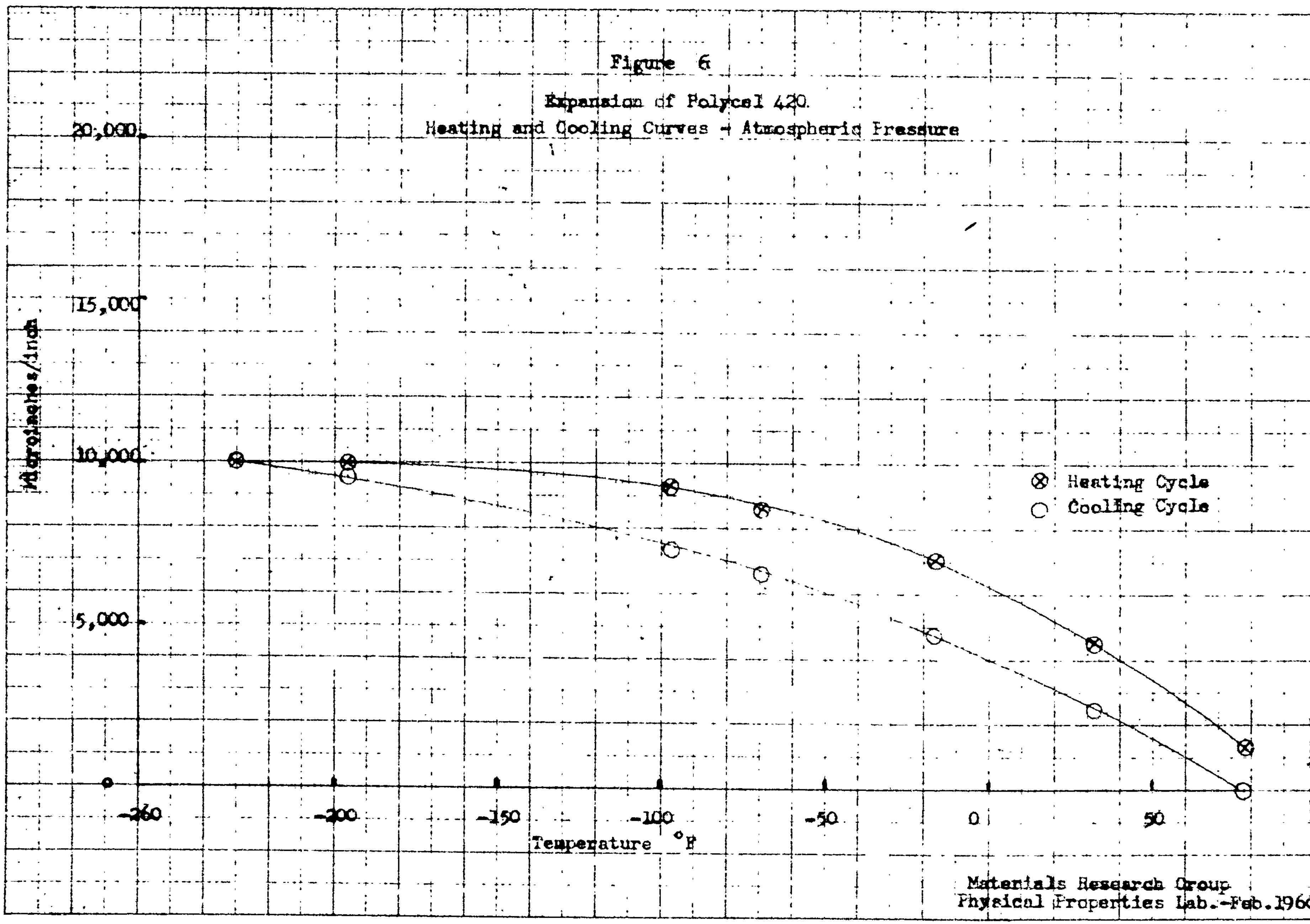
Figure 6
Expansion of Polycel 420
Heating and Cooling Curves - Atmospheric Pressure
Microinches/inch
20,000
15,000
10,000
5,000
-260
-200
-150
-100
-50
0
50
Temperature °F
Heating Cycle
Cooling Cycle
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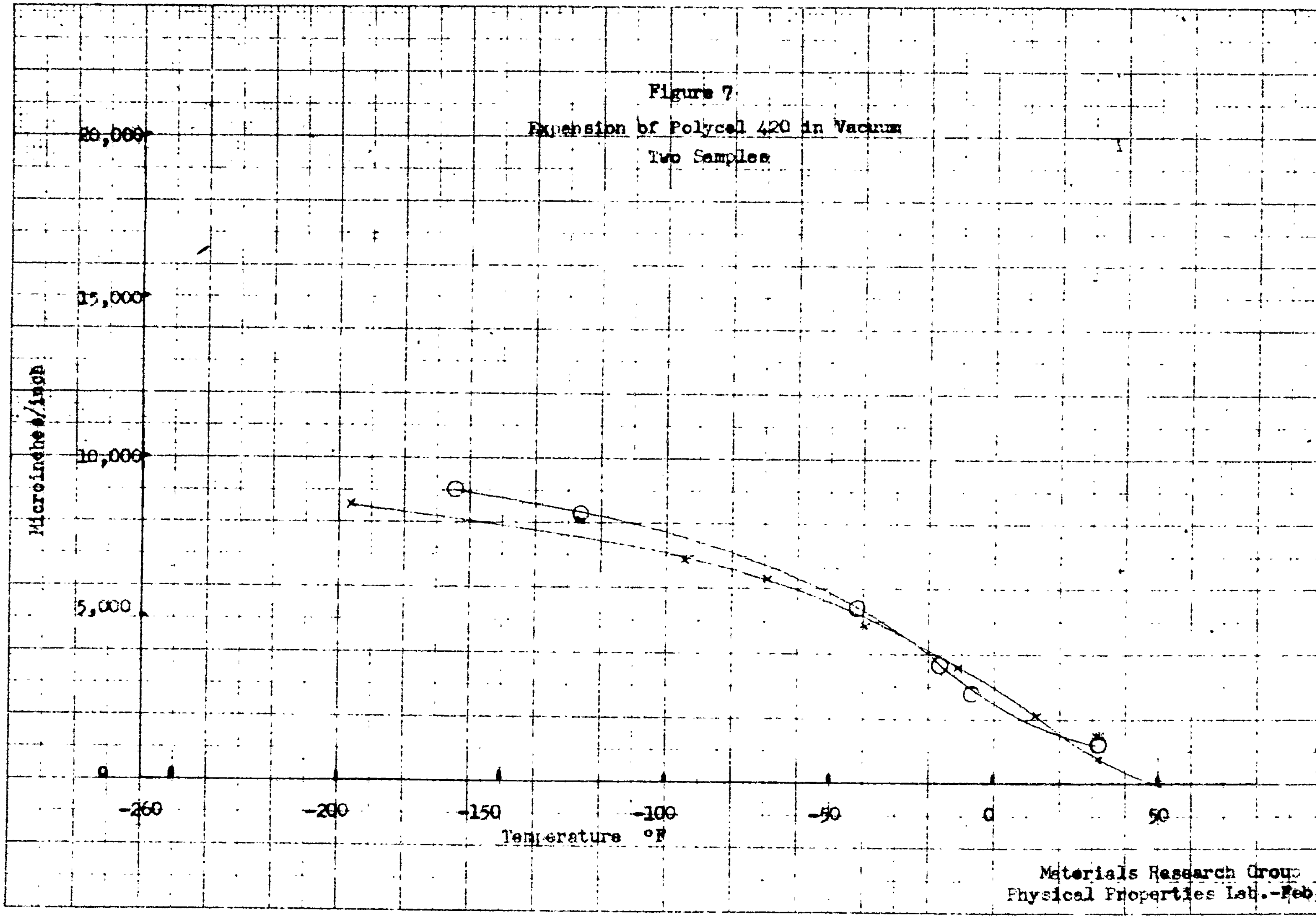

Figure 7
Expension of Polycel 420 in Vacuum
Two Samples

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